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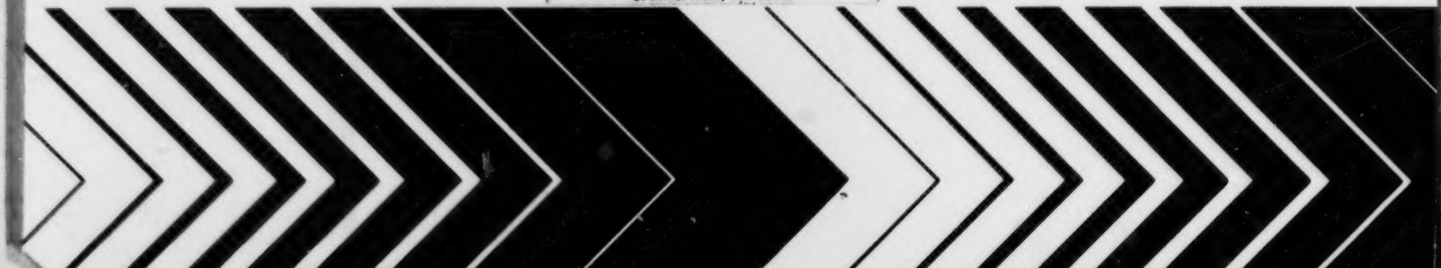

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16. ABSTRACT

This study was conducted to determine the effectiveness of nitrifying secondary effluent with rotating biological surfaces (RBS). Two municipal effluents were evaluated; one was from a high rate trickling filter and the other was from two-stage, flow through lagoon.

RBS pilot plants were installed at both of the treatment plants to provide a continuous flow of secondary treated effluent. Ammonia-nitrogen, nitrite and nitrate-nitrogen were monitored along with other chemical constituents to determine what effect a change in loading, staging, pH, alkalinity, temperature, speed of rotation, and shock loads had on the performance of the RBS.

The RBS pilot plant at the high rate trickling filter plant provided satisfactory results which showed the effect on effluent ammonia-nitrogen reductions by operational changes at the RBS pilot plant. The RBS pilot plant at the lagoon system encountered operating difficulties which resulted in an early cancellation for this phase of the project.

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NITRIFICATION OF SECONDARY MUNICIPAL WASTE EFFLUENTS BY ROTATING BIO-DISCS

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This study was concerned with the applicability of rotating biological surfaces for achieving nitrification of secondary treated effluents. The report covers the effect various parameters have on the performance of the rotating biological surfaces and their capability to respond to stress conditions.

Francis T. Mayo
Director, Municipal Environmental
Research Laboratory

PREFACE

The emergence of public cognizance of eutrophication as a problem has come about slowly over the past 15 years. The outcry relative to the so-called "death of Lake Erie" was but one evidence of concern. Nutrients in sewage effluents are partly responsible for the fertility of receiving waters, and the two macro-nutrients which play a large part in this response are nitrogen and phosphorus. Nitrogen thus ranks high as a problem constituent in waste treatment effluents. As a result, the limitation of this element in treated effluents is frequently being required.

Both high-rate trickling filters and lagoons often pass substantial quantities of ammonia-nitrogen to their receiving waters. Frequently, the original choice of these types of processes was based on their inherent simplicity. Any type of nutrient removal process added to these systems which is essentially complex would destroy the desired level of simplicity in their overall operation.

One possibility which would certainly meet the criteria for simplicity would be the rotating biological surface (RBS). This device used solely by itself could nitrify the plant effluent, or in instances where subsequent denitrification is practiced would contribute to removal of nitrogen from the effluent. The pertinent questions are: will the RBS induce sufficient nitrification, is it dependable, and what loading factors are possible?

A study of RBS nitrification had to be carried out in the field so as to utilize the actual waste effluents from the processes in question. These effluents contained natural bacterial seed and reflected the typical fluctuations in concentration and flow normally experienced at treatment facilities.

The research as envisioned involved the basic biology of nitrification as induced by the RBS system. Nitrification used in this regard is a bio-oxidation reaction requiring the culturing and attachment of the essential species of autotrophs on the contact surfaces. The organisms are known to be sensitive, and difficult to culture, and their growth response mechanisms are not well understood. While the application of RBS to the overall problem of nitrification in two select types of waste treatment is the major issue of this research, a side issue of some import must be the furthering of the knowledge of nitrifier metabolism.

ABSTRACT

This research program involved the study of biological nitrification of two different municipal waste plant effluents; one a high-rate trickling filter effluent, and the other a flow-through, two-stage, raw sewage lagoon effluent.

The effluents from each of these plants contained nitrogen compounds in the form of organic nitrogen, ammonia and more oxidized forms, up to and including nitrate. It was the objective of this research to design and build two rotating bio-disc pilot plants which were added to the effluent end of the aforementioned municipal waste plants. Operation of these pilot units was monitored to determine whether rotating bio-disc surfaces (RBS) could provide a satisfactory level of nitrification in either one or both of these waste plant effluents.

In the case of the high-rate trickling filter, the results were positive and the report considers the factors of pH, alkalinity, loading, and staging from the point of view of design of RBS systems to induce optimum nitrification.

The study at the raw sewage lagoon was exceedingly difficult to deal with. For most of the year, no ammonia-nitrogen was present in the effluent because of algae stripping. Also during the bitter cold winter, freeze-ups were common. As a result, the lagoon aspect of this project was cancelled.

This report was submitted in fulfillment of Grant No. R803407 by the University of Michigan, Department of Civil Engineering, under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers the period from January 6, 1975 to March 31, 1977. The work was completed August 31, 1977.

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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

Alk. -- alkalinity—the sum of the bicarbonate, carbonate, and hydroxide ions expressed as $CaCO_3$, mg/ℓ

BOD_5 -- 5-day, 20°C, biochemical oxygen demand, mg/ℓ

D.O. -- dissolved oxygen, mg/ℓ

gpd -- gallons per day, usually expressed on a per square foot basis

RBS -- rotating biological surface

rpm -- revolutions per minute

SS -- suspended solids

temp. -- temperature in degrees Celsius

SYMBOLS

A -- surface area, m^2

A_1 -- surface area, m^2/first stage (where subscript denotes stage)

A_i -- ammonia-nitrogen concentration at ith stage, mg/ℓ

B_i -- nitrite-nitrogen concentration, mg/ℓ

C -- bulk fluid substrate concentration mg/ℓ

C_i -- nitrate-nitrogen concentration at ith stage, mg/ℓ

C_o -- initial substrate concentration, mg/ℓ

g -- grams

ABBREVIATIONS AND SYMBOLS (Concluded)

K_s -- half-saturation coefficient, mg/ℓ

K_{sb} -- half-saturation coefficient for *Nitrobacter*, mg/ℓ

K_{ss} -- half-saturation coefficient for *Nitrosomonas*, mg/ℓ

K_1 -- rate coefficient for ammonia oxidation, mg/ℓ/hr

K_2 -- rate coefficient for nitrite oxidation, mg/ℓ/hr

mg -- milligrams

N_2 -- nitrogen gas

NO_2 -- nitrite-nitrogen, expressed as N, mg/ℓ

NO_3 -- nitrate-nitrogen, expressed as N, mg/ℓ

N_{ox} -- sum of nitrite plus nitrate, expressed as N, mg/ℓ

NH_3 -- ammonia-nitrogen, expressed as N, mg/ℓ

pH -- log (base 10) reciprocal of hydrogen ion concentration, g/ℓ

Q -- flow rate, ℓ/hr

R_{ss} -- steady state removal—biological removal of substrate under relatively constant flow and load

R_{sl} -- shock load removal—that additional removal above the R_{ss} value when a shock load is imposed

V -- volume of a stage, ℓ

X -- biomass, mg/m^2

Y -- yield coefficient, mg cells/mg substrate

μ -- specific growth rate, 1/hr

μ_{max} -- maximum specific growth rate, 1/hr

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SECTION 1

INTRODUCTION

GENERAL

This report summarizes the work done over a 2-1/2-year period in the study of biological nitrification and the use of rotating discs to enhance this natural bio-oxidation process. The work has utilized the effluent from a municipal high-rate trickling filter as the basic substrate for the nitrifiers. Many of the observations have been checked or verified in the laboratory where a synthetic substrate has been used.

Additional work using a municipal flow-through-type lagoon system was attempted. Insufficient ammonia nitrogen was present for sustained operation, and inclement weather made continuous operation exceedingly difficult to maintain. As a result, this portion of the work was curtailed.

When this research was first contemplated there were many facets of biodisc nitrification which were quite obscure. Many of these problems have been cleared up only to generate new questions. However, there is little doubt that progress in the understanding of biological nitrification is much more advanced than was true when the work was initiated.

NITRIFICATION

Nitrification can probably best be defined by reference to the usual nitrogen cycle depicted in most beginning courses in science or biology. Figure 1 indicates such a cycle in which plant life is the general source of sustenance for animal life. Organic matter subsequently passes on by death of the cellular matter or the production of waste products to become the raw ingredients for the first stage of the cycle, namely, that of ammonification. Many organisms hydrolyze complex organic matter to produce the breakdown of protein through peptones, peptides, and eventually release of ammonia. The ammonia is generally oxidized by a relatively exclusive and restrictive group of organisms which are strict autotrophs. Their entire energy resources comes from the oxidation of ammonia to nitrites and nitrites to nitrates. The first step is carried on by species of *Nitrosomonas*

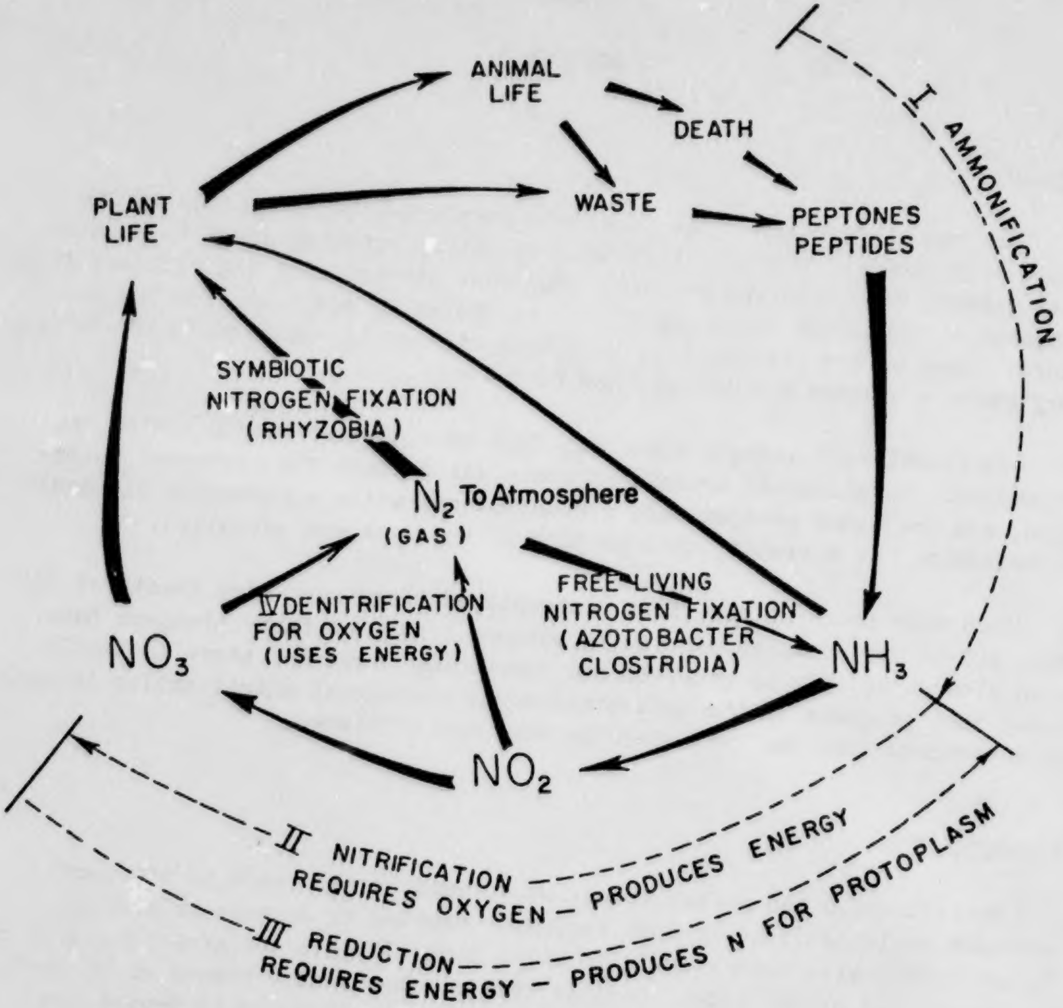
ANIMAL LIFE
DEATH
PLANT LIFE
WASTE
PEPTONES PEPTIDES
I AMMONIFICATION
SYMBIOTIC NITROGEN FIXATION (RHYZOBIA)
N2 To Atmosphere (GAS)
IV DENITRIFICATION FOR OXYGEN (USES ENERGY)
FREE LIVING NITROGEN FIXATION (AZOTOBACTER CLOSTRIDIA)
NO3
NH3
NO2
II NITRIFICATION REQUIRES OXYGEN – PRODUCES ENERGY
III REDUCTION REQUIRES ENERGY – PRODUCES N FOR PROTOPLASM

Figure 1. Nitrogen cycle.

and Nitrosococcus and the second step by Nitrobacter. Recent evidence in the literature indicates that certain fungal forms can also carry on this process. These are apparently heterotrophs and of less importance in nature than the true bacterial forms. Nitrates, of course, are a major fertilizing element for much farm and garden produce. With the return of the nitrogen in the form of nitrate to the plant, the cycle starts over again.

Nitrification may now be defined from Figure 1 as that step in the nitrogen cycle which converts the ammonia to the more oxidized forms of nitrite and nitrate. It is only by going through this step that the fertility of the nitrogen compounds may be destroyed by the succeeding step of denitrification. There is no simple, straightforward mechanism for converting ammonia directly into free nitrogen gas in nature. Similarly, the reduction of nitrite and nitrate back to ammonia would merely recycle the nitrogen without reducing it in quantity.

The nitrogen cycle has other ramifications, of course. Nitrogen from the atmosphere can be fixed in the soil, and normally is, by many symbiotic forms of organisms living in and on the root systems of legumes. To a lesser extent, free nitrogen is also fixed in the living cells of Azotobacter and the anaerobic Clostridia. Recent studies have shown that blue-green algae can do the same things in the aqueous environment (1). When such organisms die and decompose, the nitrogen is released as ammonia to the environment.

There are a great many organisms that will attack nitrites or nitrates and reduce such salts to ammonia for the purposes of obtaining nitrogen to build protoplasm. This, of course, takes energy which must be put into the system, obviously from other sources. Many organisms will also denitrify. The step of denitrification as indicated on the chart is usually carried on primarily for purposes of obtaining oxygen. This step, too, would require energy from other biochemical systems in order to proceed. The denitrification step would take the soluble nitrate or nitrite, and produce nitrogen gas as a final product. This mechanism is the only technique which has been identified to date as returning the nutritive building blocks of fertilizing forms of nitrogen back to the original source of the nitrogen, namely, the atmosphere.

The history of the study of the nitrification process is extremely interesting for it details some of the most tedious research work done by early microbiologists in the formative years of the science of bacteriology. Careful study of their research is quite worthwhile for it illustrates facts which we seem to be rediscovering today.

In 1877 Schloesing and Muntz, in a very simple experiment, demonstrated conclusively the biological origin of the nitrification process (2). They used, for this purpose, a tube 1 m long filled with sand and chalk, previously sterilized by incineration. Sewage water was poured daily into the upper end of the tube. For 20 days the ammonia content of the effluent remained constant. Then suddenly nitrate made its appearance and the ammonia content fell to zero. The nitrification process once started, continued for four months and then the investigators tried the effects of disinfection on the reaction and a current of chloroform was drawn through the tube. This had the effect of killing the organisms and once more ammonia came through the tube. Nitrates were then restored by the application of washings from garden soil. These experiments noted that alkaline conditions were necessary for the production of nitrification and that the reaction required a plentiful excess of oxygen. It should be noted that their column contained chalk, calcium carbonate, and in addition that it took 20 days for the nitrifiers to sufficiently establish themselves to produce good nitrification. As a result, it seems apparent that these are slow growing organisms in contrast to many other bacterial forms, as for example the ammonifiers in the experimental tube (such organisms showed their effects the first day). Nitrifying organisms, however, could not be isolated by experimenters for many years, though many investigators tried. Somehow or other, this step seemed to be unexpectedly difficult.

Winogradsky was the first to become convinced that the gelatin plate method which had proved so successful for the isolation of disease germs was unsuited to the isolation of nitrifying organisms. He, therefore, tried an extremely simple liquid substrate consisting of a water solution of four inorganic salts plus potassium tartrate which was to be the source of carbon (3). No growth at all was experienced. He then proceeded to eliminate first one and then the other of the items from the medium with no growth resulting until finally he left out the potassium tartrate. He was then immediately gratified to see the culture produce intense nitrification.

Subsequently, then, Winogradsky employed a solid medium in which the appropriate solution of salts was solidified by silicic acid. On this so-called silicate jelly, colonies of nitrifying organisms alone developed and could easily be obtained free from other bacteria. When streaked on a slide and stained, the organism Nitrosomonas appeared to be a flagellated rod, Figure 2. A typical medium for isolation of nitrifying organisms has been given by Heukelekian (4). To a liter of distilled water add:

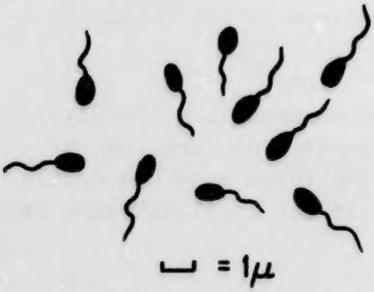

Figure 2. Nitrosomonas.

Ammonium bicarbonate - 0.2 gram
Dipotassium phosphate - 1.0 gram
Sodium chloride - 1.0 gram

Magnesium sulfate - 0.5 gram
Ferrous sulfate - trace

Into such a medium one would introduce his garden soil, sewage, activated sludge, etc., incubate for a period of time, and after repeated transfers into successive tubes of this medium, the nitrifiers alone would persist.

Reference again to Winogradsky's experiments indicates that he observed that the oxidation of ammonia to nitrite always preceded that of nitrite to nitrate; and that, as a rule, the nitrate did not begin to accumulate in considerable quantities while any amount of ammonia remained unoxidized. Winogradsky concluded that two organisms, or at least two groups of organisms were concerned in the nitrification process. By setting up his inorganic substrates, with first ammonia but no nitrite and second with nitrite but no ammonia he did succeed in isolating two types of organisms.

While these differed morphologically according to the part of the world from which they came, all seemed to be alike in their chemical behavior in the requirement of the same substrate conditions. Namely: these are, the presence of a salt of ammonia or nitrite, strongly aerobic conditions, and the presence of carbonates in the medium. Under proper conditions, therefore, the reactions are catalyzed by the organisms with the production of a great deal of energy. The first step from ammonia to nitrite produces 79,000 cal/mole, while the second step of nitrite to nitrate produces 21,600 cal/mole (based on heat of combustion). Meyerhof has shown that the organisms manage to utilize about 5% of the energy released by the reaction and that approximately 95% of the energy liberated appears as heat (5). It is this fact that is responsible for the extremely low growth rate of nitrifying organisms. In turn the low growth rate makes the development of useful amounts of culture a difficult step. It is at this point that the potential conservative features of the rotating disc system suggest its use in studying nitrification.

DESCRIPTION OF BIO-DISC PROCESS

Prior to 1967, there was little information or familiarity in the U.S.A. with the bio-disc system of waste treatment. At about that time, pilot plant work was undertaken on several fronts which eventually led to full-scale adoptions and a better knowledge of the bio-disc process (6-9):

The use of the bio-disc in Europe, however, and particularly in Germany has been quite extensive, and over 700 installations (some with more than 25 years of experience) are presently in operation. Most of them are small, but the municipal plant at Donauischigen, West Germany, serves about

100,000 people.

In essence, the bio-disc process consists of a series of closely spaced discs mounted on a shaft which in turn is supported just above the surface of the waste to be treated. The shaft and associated discs rotate slowly (2-6 rpm) so that each segment of the disc pack is alternately submerged to adsorb food and then raised out of the waste into the air for oxidation purposes. The waste passing between the discs flows parallel to the adjacent disc surfaces which support a luxurious biological flora. The discs rotate slowly but impart a lifting action through the drag forces developed. This head imparts a pumping action to the liquid, which in turn is induced to circulate numerous times over the submerged quadrants of the discs in passing through each stage of treatment. Incidently, it is unimportant whether the disc shaft is transverse to the flow pattern or parallel to it. The velocities of the fliud induced by rotation of the disc-pack are dominant over any velocity created by the flowing liquid. Likewise, there may be one or several stages of discs on one shaft. As long as the tank itself is compartmented to fit the stages needed and the speed of rotation is governed by the critical stage, the system will perform optimally.

When several stages of discs are utilized, the many narrow pathways through the total unit are long and tortuous and the process in general can most simply be described as being a horizontal trickling filter.

If the biomass exposed to the waste is scraped off the discs at one or more points, it is possible to estimate the amount of growth involved in the process. It is always heaviest in early stages and lighter in later stages. In typical situations, concentrations of over 100,000 mg/ℓ have been measured. Normal patterns however, indicate wide differences between stages and within stages. Volatile solids are usually low indicating that some aerobic digestion has taken place.

In summary, the bio-disc process is normally a secondary treatment system. Detention periods vary from about 7 min/stage to 30 min/stage. The process has a low F/M ratio and yields good BOD removals. There is a sludge developed which represents sloughings from the disc system. These sludge solids must be removed by a process of clarification. The sludge settles easily and rapidly and disposal can be affected by any technique normally used in trickling filter technology. In operation, the bio-disc has the head loss characteristics of the activated sludge process, and yet there are no associated problems of recirculation or pumping; bulking, and foaming are completely eliminated. Of course, the piping, valving, pumps, and metering problems associated with the above are likewise eliminated.

HISTORICAL DEVELOPMENT OF RBS

A recent paper presents a brief historical review from which the following has been extracted with a few modifications (6).

> The rotating biological disc is the accumulation of many separate but related ideas. In Europe its designation of "Immersion Drip Filter" is credited by Hartmann to Professor Pöpel (10). In this country in recent years the unit has been variously referred to as the RBC (rotating Biological contractor), the RBS (rotating biological surface), and bio-surf. Buswell evaluated a unit of this type back in 1929 and he referred to the unit as a biological wheel (11). Apparently an experimental unit was developed by Paige and Jones Chemical Company under patents held by A. T. Maltby filed in October of 1928 (12) and granted June 23, 1931.
>
> According to Hartmann (10) the original thought behind the unit should be credited to Travis who in 1901 tried to increase the efficiency of his "Hydrolytic tank," a precursor of the Imhoff tank, by hanging thin wooden strips in the settling compartment. These strips he designated as "colloid catchers," and he assumed that through the mechanism of adsorption, the cloudy nonsettling portion of the sewage could be removed. After a period of accumulation the solids adsorbed on the wooden slats were supposed to reach a thickness and weight such that they would slough off the slats and fall into the digestion hopper. Unfortunately, while the solids did accumulate they didn't always slough. In addition, decomposition of the older portions of the deposits invariably reduced the quality of the tank effluent. Just after the slats were cleaned, the tank effluent was observed to be best.
>
> From such observations came two divergent ideas. Buswell was convinced that the slime was biological in nature and that its rather immediate removal from the slats was important. To this end he proceeded with experiments which involved shaking the slats. The idea of motion of the biological support finally culminated in the biological wheel and the Maltby patent.
>
> Along a somewhat different vein of thought, C. C. Hays of Waco, Texas, worked out the principle of contact aeration. His basic premise was that decomposition of the older deposits of slime could be prevented with the presence of diffused air below the wooden slats. In practice, the wooden slats became cement-asbestos sheets. While in this country the Hay's process was known as contact aeration, in Europe the process was called an immersion filter. To the experts there, the idea merely involved

> a trickling filter which was completely immersed. From this beginning, it was a logical step some years later for Professor Pöpel to view the bio-discs rising from the waste with sewage dripping in thin films over the emerging slime and to conclude that this apparatus should be called an immersion drip-filter (Tauchtropfkörpern).

In this paper, further references to the unit will designate this treatment device as a rotating biological surface (RBS).

Buswell's report of 1928 (11) concluded that there were three major advantages of the RBS.

(1) The actual area occupied by the unit was about 1/10 of that required for a standard rate trickling filter.

(2) The power cost was low compared to activated sludge.

(3) Nitrification was accomplished.

To bring this history up to the present, it must be stated that European discs are 1, 2, and 3 m in diameter and about 12.5 mm thick. Discs of the 3 m dimension were briefly installed in the U.S.A. These shifted due to competitive forces to 3.3-3.5 m (11-11.5 ft) discs also 12.5 mm thick. This change was short lived and has culminated in a much thinner polyethylene deformed disc. (The deformations augment the area and generate the necessary stiffness in the thin sheets.)

BIOLOGICAL NITRIFICATION USING RBS

While the major thrust of this research has been to study the application of the RBS to the nitrification of high rate trickling filter effluents and sewage lagoons, nevertheless some aspects of the basic nitrification mechanism have unavoidably been interjected into the study. These concepts are probably of wider application than to the RBS operation alone. Nevertheless nitrification on the RBS is the primary objective.

Buswell's work in 1929 referred to the fact that nitrification took place with the biological wheel (11). Unfortunately no figures were given by which the completeness of the reaction could be measured. The 1967-68 work previously referred to (6) indicated strong nitrification at reduced flow loadings 52 ℓ/m^2/day (for settled domestic sewage using three stages of treatment). Much additional evidence has suggested that some nitrification would take place on an RBS unit. The question therefore raised was, to what extent would the reaction proceed, how environmentally sensitive was the response, was the culture subject to wash-out at high rates of flow and could it be destroyed by shock loads (13-18)?

Certainly logic would dictate that a culture fixed to a rotating surface could be much more dependable and easier to utilize than would such a culture if it were free in an uncontrolled suspension. On the other hand, it might be anticipated that the lag time in start-up of a disc in comparison to a suspended culture system could be greater. This might be expected since the raw disc system must induce a relatively high shear region immediately adjacent to the disc. Nitrifiers are not noted for heavy encapsulation and as a result much of the seeding the disc receives could wash away rather than becoming attached.

In contrast a system maintaining a relatively modest level of chemical or biological floc would tend to trap more of the seed organisms. Therefore, in this research it seemed important that start-up time should be examined. On the other hand, direct comparison of the disc system to suspended culture systems would have to be considered beyond the scope of the work.

There was no question initially relative to the need for seeding especially when no seed was present in the influent (such as in a laboratory system). However, the acceptable pattern for optimally seeding such a system seemed to be quite unclear. Other related questions were also of obvious importance. For example, in this connection, how significant is pH and alkalinity? If a critical level for these factors exists will its absence affect seeding materially and might not this fact prevent or retard start-up?

The present project was inaugurated January 6, 1975, and designed to run for two years during which time two types of municipal waste plant effluents would be utilized as previously noted. How would their effluents respond to the RBS when the process was added as a pilot unit at the discharge end of each type of plant? As a result of the facts just presented the nature of the treatment plants and their effluents became critical parameters in the research as it developed.

SECTION 2

CONCLUSIONS

1. Experiences with an underloaded. high-rate trickling filter and a two-stage, flow-through lagoon indicate no difficulty in start-up of a second-stage nitrification using the bio-disc.

2. The ammonia-N concentration was never appreciable in the lagoon effluent at Genoa, Ohio (two-stage, flow-through lagoon). When a synthetic ammonia feed was applied to the pilot plant, the discs responded by generating a culture of nitrifying organisms.

3. High algal counts, low ammonia levels, precipitating calcium carbonate, and extremely low temperatures forced curtailment of the work at Genoa.

4. The Saline, Michigan Wastewater Treatment Plant (high-rate trickling filter) had a respectable ammonia-N content in its effluent at all times (avg. 16.3 mg/ℓ as N). The bio-disc (RBS) readily developed a good nitrifying culture. The system should be rated excellent as a means of accomplishing the objective of nitrification.

5. Over the two-year operating period of this research project, 0.6 m and 1.2 m disc systems (RBS) were operated in parallel. The results in all cases were similar enough that they could have been produced by one system.

6. Laboratory units never performed like the field units in terms of start-up, biomass buildup, uniformity of removal, and environmental responses dependent on bio-film thickness. True performance research then should be carried on in the field with actual wastewaters and normal seeding.

7. The flow testing range of this work extended from 0.25 gpd/ft^2 (10.2 ℓ/m^2/day) up through 6 gpd/ft^2 (244 ℓ/m^2/day) on six stages of discs. Removal of ammonia-N exceeded 70% at all loadings.

8. Results indicate that for a given area of discs, the more stages used the more consistent the results.

9. Short-term environmental changes versus long-term changes are indicated as needing better definition.

10. pH and alkalinity relations are shown to be typical of suspended culture nitrification work.

11. The weight of ammonia-N removal by a given area of discs increases as the flow increases up to a limiting value of 3 ℓ/m^2/day.

12. Speed of revolution was checked for optimum oxygen uptake conditions, 3.5 mg/ℓ of D.O. in the bulk fluid seemed to be a useful figure. At and above this level, sufficient D.O. existed in the bulk fluid to provide the driving force necessary to satisfy the requirements of the bio-films developed in this work.

13. The diffusional limitations of the bio-film were demonstrated in several ways. At present, the nitrifying biomass in RBS work cannot be defined except by approximation.

14. The response of a normal series of bio-discs to a shock load is disappointing, the problem being one of understanding the nature of the nitrifying organisms more than anything else.

15. A simplified kinetic approach to the bio-disc problem appears to be necessary at this time because of the problems encountered in defining biomass and diffusion.

SECTION 3

RECOMMENDATIONS

FIELD WORK

1. It is important that continued work in the field be carried out for purposes of longer operational patterns at increased flow levels.

2. Field study of multistage units should likewise be continued to further define the factors governing the employment of staging. These factors will influence further development.

3. Alternation of flow by automatic valving may yield desirable factors for future study under some conditions of flow or loading.

4. Optimization of biomass weight and thickness either chemically or mechanically may lead to control of diffusional problems.

5. Once the biomass has been optimized, then fine tuning of environmental conditions would be quite fruitful. Potential exists for such items as D.O. control of bio-disc speed and maximizing driving force by control of the ammonia-N level in the first and second stages of discs. These and other such concepts will produce worthwhile modifications to an already highly dependable nitrification device.

LABORATORY WORK

1. The bio-film is still a major problem in the use of mathematical models. Controlled feeding in the laboratory and extensive analysis of the slime layers developed should enable the separation of autotrophic and heterotrophic activities and the definition of the interaction and inhibitions generated.

2. A similar extensive study into the nature of the mechanism by which the organisms attach themselves to a surface would be very useful.

3. Following optimization, a study of toxicity and inhibitory compounds would be extremely fruitful.

SECTION 4

EXPERIMENTAL PROCEDURES

SALINE WASTE TREATMENT SYSTEM

The Saline Waste Treatment Plant processes about (3.800 m^3/day) of essentially domestic wastes. The wastewater receives grit removal and primary clarification. Chemical is added to the grit chamber for phosphorus removal. After primary clarification the waste passes through a two-stage trickling filter, final clarification and thence to sand filtration, chlorination and discharge to the Saline River (see Figure 3). The pilot unit for the RBS system was inserted between the final clarifiers and the sand filters. A submersible pump was placed in a channel between these two treatment units and a plastic hose was used to conduct the necessary flow to the RBS site. Discharge from the RBS was run by a plastic pipe back to the final clarifiers.

This pilot plant influent was a typical secondary effluent and was sampled about three times per week during pilot runs. The city water originates in wells and as a result is fairly stable and uniform in quality. There is a large industrial plastics operation in the town and as a result of a strike a marked drop in ammonia level was noted for the duration of the strike. Other than that instance the level of ammonia was high but seemed to be higher in winter and lower in spring and summer. Monthly, high, low, and mean values are given in Table 1 and plotted in Figure 4.

Reference to Figure 4 indicates the existence of a sinusoidal trend in the influent ammonia concentration. At least for the period of study, peak concentrations were reached in January or February and the lowest concentration was reached in July. No ready explanation can be offered for this observation. The possibility exists that sludge handling operations could be responsible for the apparent trend and that a change in this operation could alter the entire situation.

If the temperature cycle of the pilot plant influent is taken into account (see Figure 5), it is obvious that the highest ammonia concentrations and the lowest temperatures coincide and similarly that lowest ammonia concentrations occur with the highest temperatures. This produced a difficult

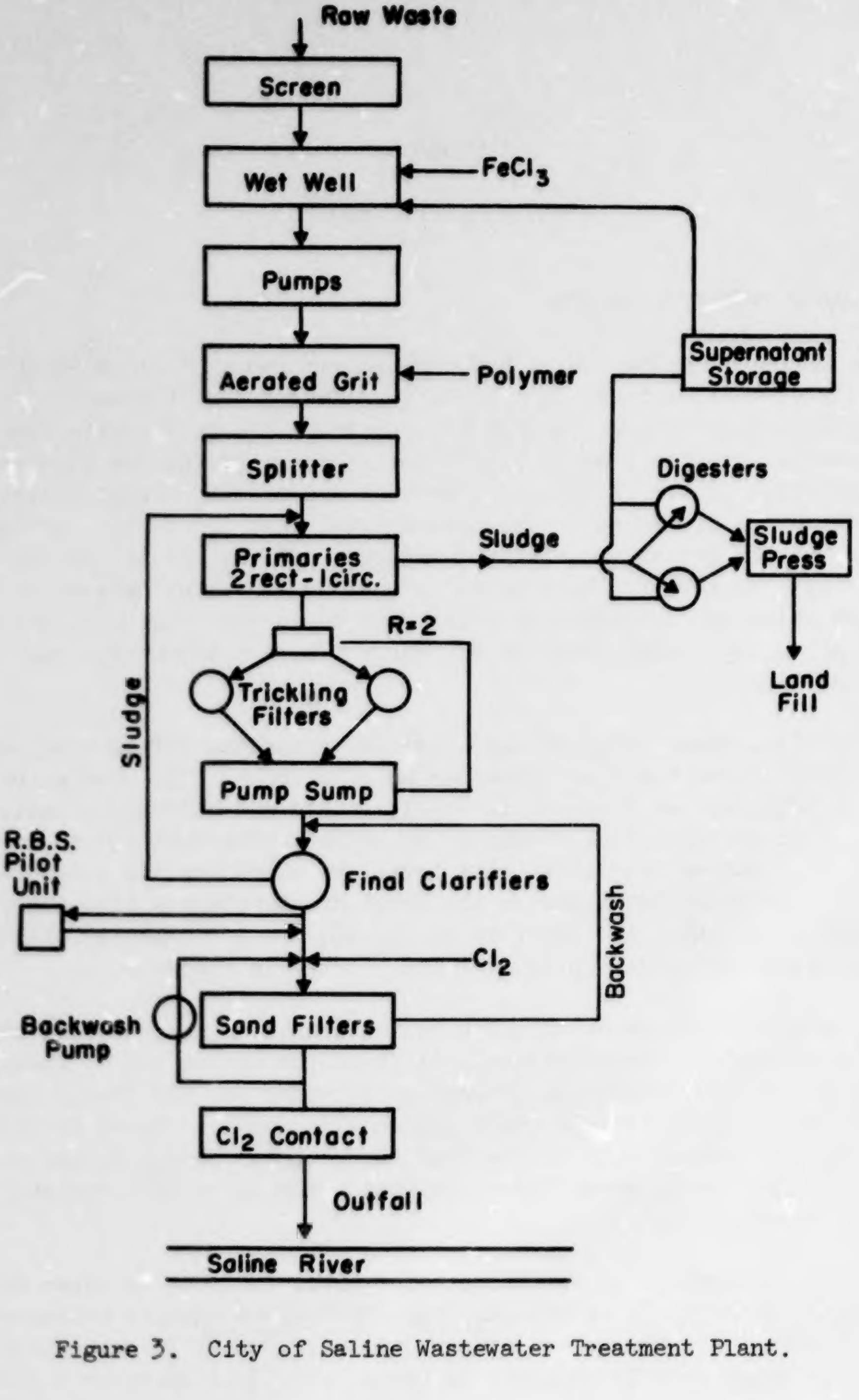
Raw Waste
Screen
Wet Well
FeCl3
Pumps
Supernatant Storage
Aerated Grit
Polymer
Splitter
Digesters
Sludge
Primaries 2 rect - 1 circ.
Sludge Press
R=2
Land Fill
Trickling Filters
Sludge
Pump Sump
R.B.S. Pilot Unit
Final Clarifiers
Backwash
Cl2
Backwash Pump
Sand Filters
Cl2 Contact
Outfall
Saline River

Figure 3. City of Saline Wastewater Treatment Plant.

TABLE 1. INORGANIC NITROGEN FRACTIONS IN SALINE PILOT PLANT INFLUENT

Year	Month	No. of samples	NH_3-N mg/ℓ max.	min.	avg.	(NO_2-N + NO_3-N mg/ℓ)* avg.
1975	Aug	7	16.2	9.4	12.2	3.3
1975	Sept	9	14.0	11.7	12.6	1.7
1975	Oct	13	20.0	9.4	14.2	5.7
1975	Nov	8	20.0	12.6	15.6	6.4
1975	Dec	7	19.7	12.8	15.4	4.6
1976	Jan	11	22.2	13.4	16.6	3.3
1976	Feb	10	19.8	5.4	13.1	2.8
1976	Mar	5	15.6	9.8	12.1	1.5
1976	Apr	4	19.0	15.0	16.4	4.6
1976	May	6	13.8	8.6	11.5	3.8
1976	June	8	21.5	8.0	13.8	3.1
1976	July	6	17.8	6.9	10.4	4.5
1976	Aug	10	23.0	7.7	13.0	3.0
1976	Sept	11	26.8	10.0	16.2	4.4
1976	Oct	14	24.1	8.9	15.2	4.1
1976	Nov	3	24.1	15.2	19.3	4.5
1976	Dec	24	31.3	11.8	21.3	4.5
1977	Jan	5	23.3	16.8	20.5	4.1
1977	Feb	8	30.3	14.8	22.5	3.0
1977	Mar	13	23.8	15.0	18.9	5.4
		181			$\bar{x}$ = 16.3	3.9

*The sum of NO_2-N + NO_3-N will be referred to as N_{ox} at further points in this report except when looking at NO_2 alone.

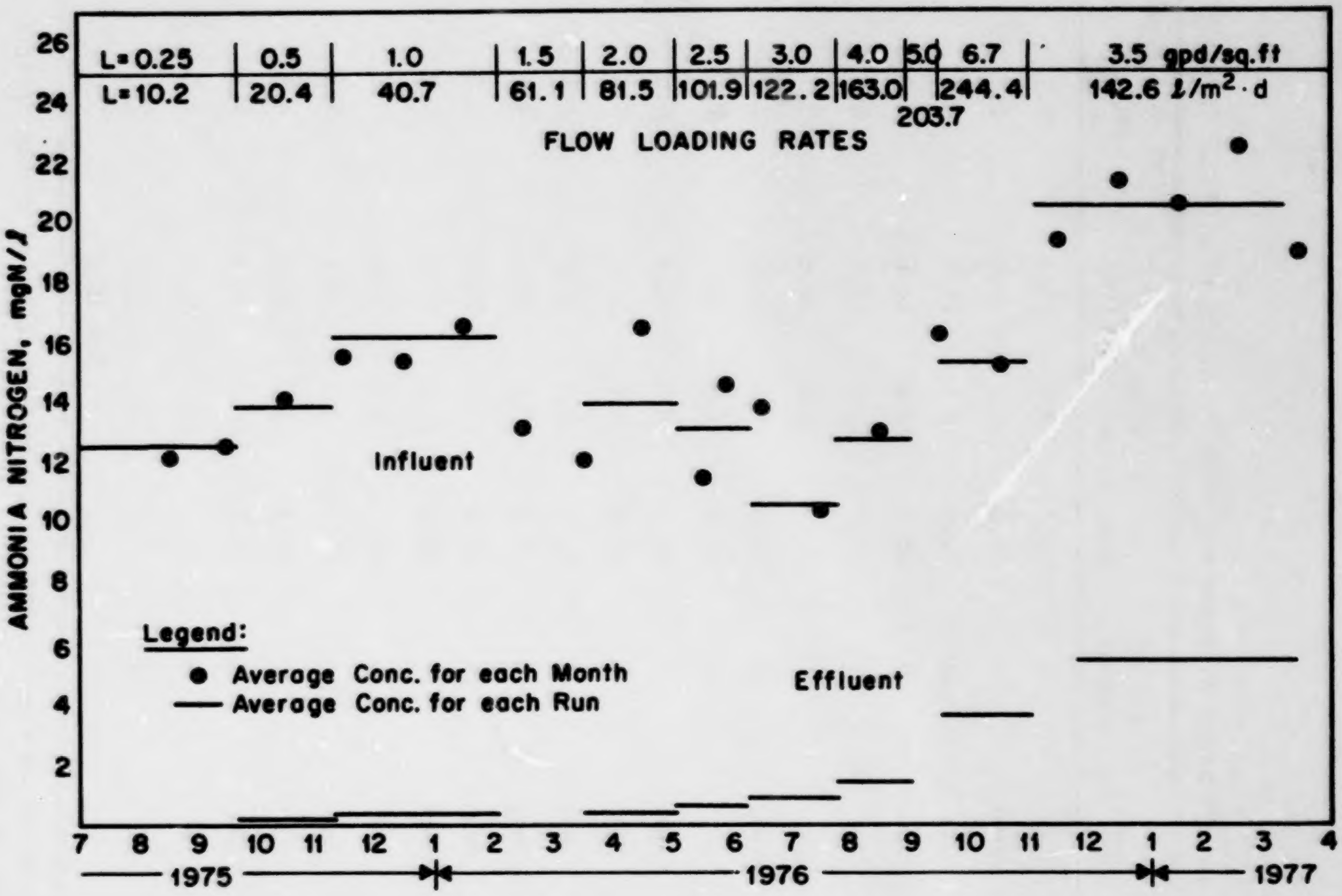

Figure 4. Summary of nitrification performance versus hydraulic loading rates at Saline, Michigan.

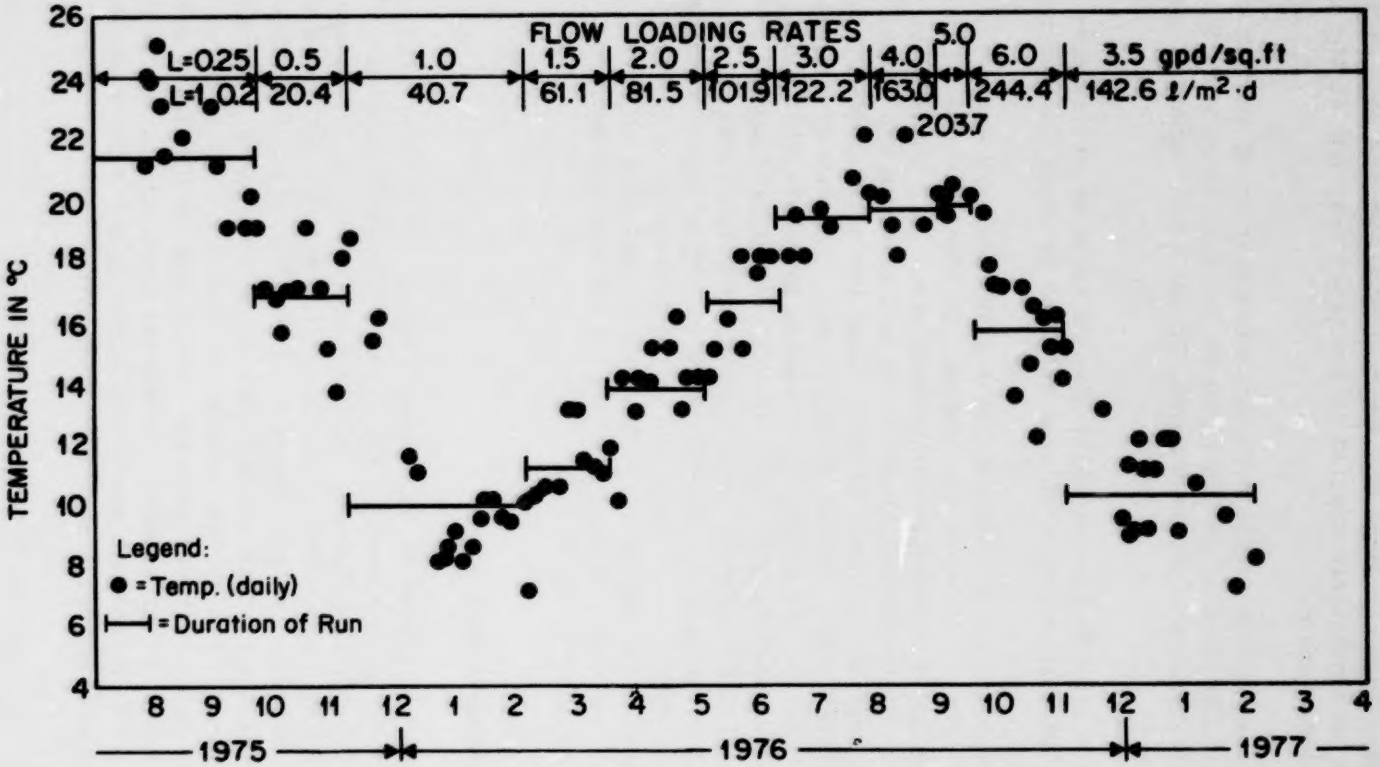

Figure 5. Summary of temperature values versus hydraulic loading rates at Saline.

situation in the Saline pilot plant during the final run. Certainly the unit was stressed severely since the run took place at the peak of the observed ammonia concentrations applied to the pilot unit and at the low point of the yearly temperature.

Figure 4 also indicates the effluent concentration of ammonia values observed. The results during the final run do increase because of the above factors. One significant feature however, is the total amount of ammonia removed.

This factor remains exceptionally high in spite of the adverse conditions noted. This circumstance will be referred to later in this report.

Table 1 also indicates that the pilot plant influent generally contained a moderate but continuous level of nitrate. It should be emphasized that this fact seems to be independent of temperature. This observation implies that a low rate of nitrification exists at all times in the trickling filter portion of the treatment cycle. Table 1 gives the monthly mean values for (nitrate + nitrite) over a period of the study. The average for 181 observations was 3.9 mg/ℓ. The consistent presence of substantial quantities of oxidized nitrogen suggests that seed organisms were continuously present in the influent of the RBS system. As a result the pilot plant responded dependably in all respects which were considered a function of seeding. Start-up or a shift in operating level presented no problem or challenge to the Saline RBS system. Any change in procedure required time to permit biomass adjustment, but the plant in general appeared healthy and performed well during the two-year testing period.

GENOA WASTE TREATMENT SYSTEM

Genoa, Ohio was chosen as the sewage lagoon system to be studied. The city lies about 72 km southeast of Ann Arbor. Treatment consists of two facultative, flow-through lagoons, each having an area of 2.7 ha and a BOD loading of 28 kg/ha. The plant effluent is discharged directly to the Tousaint River a few kilometers from Lake Erie. The final discharge is not chlorinated. The design data is indicated below in Table 2. The plan view and cross section of this system is shown in Figure 6. As is shown in the figure, the RBS pilot unit was inserted in the plan by placing a submersible pump in the final effluent manhole. A sandbag provided the necessary sump. Once assembled, the pilot unit was placed directly above the manhole and a shed-like structure was built over the whole unit.

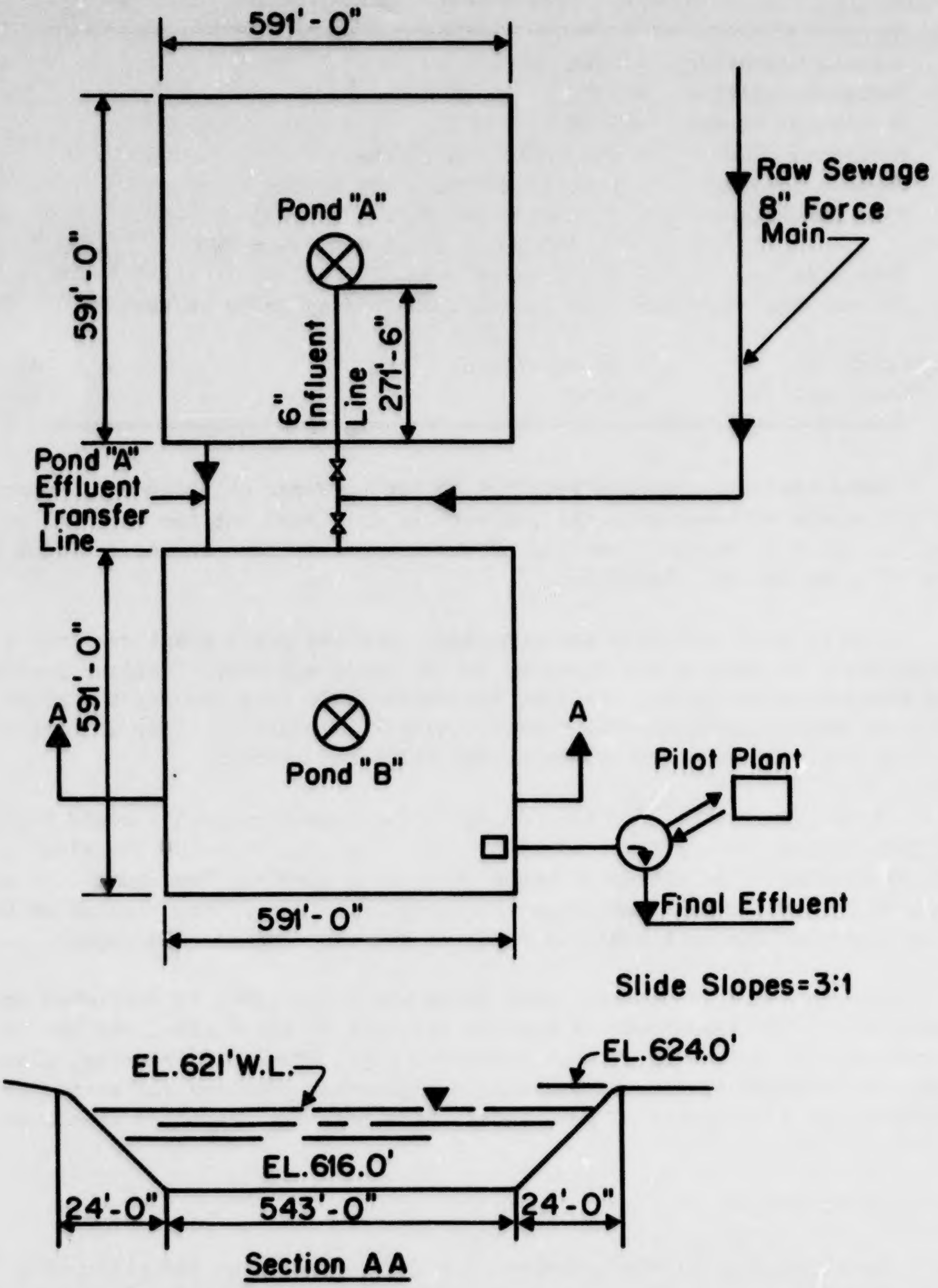
591'-0"
Raw Sewage
8" Force
Main
Pond "A"
591'-0"
6" Influent Line
271'-6"
Pond "A" Effluent Transfer Line
591'-0"
A
A
Pond "B"
Pilot Plant
Final Effluent
591'-0"
Slide Slopes=3:1
EL.621'W.L.
EL.624.0'
EL.616.0'
24'-0"
543'-0"
24'-0"
Section AA

Figure 6. Genoa wastewater treatment.

TABLE 2. DESIGN DATA - GENOA, OHIO

Initial Operation	- 1966
Design Population	- 2500
Population Served	- 2000
Estimated Flow	- (0.2 MGD) 756 m^3/day
Organic Loading	- (240 lb BOD/day) 109 kg/day
Pond Dimensions	- (543 ft x 543 ft x 5 ft SWD) 165.5 m x 165.5 m x 1.5 m SWD
Pond Area	- (6.77 acres each) 2.7 ha
Primary Pond Loading	- (1.2 lb BOD/1000 ft^2/day or 50 lb/acre/day) 28.4 kg/ha
Detention	- 88 days total
Disinfection	- None

There was some question relative to the presence or absence of ammonia in this waste effluent when the project was initiated but the work was pursued in order to be quite certain of the treatment plant characteristics and the effluent derived therefrom.

Intense algal activity was prevalent when the pilot plant was activated. As a result no ammonia was observed in the Genoa effluent. Calcium carbonate deposition was heavy. In fact the submersible pump feeding the pilot unit was totally plugged with deposits almost immediately after initiation of activity. Maintenance became a very difficult problem.

It was hoped that with the coming of fall weather ammonia would begin to pass through the system. On that basis, ammonium chloride was added to the pilot plant disc system by means of a small chemical feed pump. It was thought that this would encourage the growth of a nitrifying biomass on the discs and thus the unit would be ready if and when ammonia did appear.

Data on Genoa is sparse. That which was accumulated is presented in Appendix C. The appearance of ammonia was late in the winter, was low in concentration, and never without extensive algal biomass. Freezing, plugging, and supplementation of ammonia were constant problems and seemed to preclude the development of good data. This unit was therefore abandoned.

PILOT PLANT DESIGN

The first step in the research plan was to design an RBS pilot unit which would provide sufficient size and flexibility to yield the desired information. The unit had to be large enough to yield data which could be extrapolated to a full scale prototype. It had to be large enough so that continuous sampling of flow between stages would have no effects on any observations that might be made. At the same time each unit had to be easily transported by truck, require no more than a 100-V lighting circuit as an electrical service and have maximum flexibility.

The basic disc material in commercial units now consists of a thin polyethylene which has been deformed for added strength and rigidity. These deformations do provide added area, but for purposes of flexibility in research, can be dispensed with. Flat discs are more general, can be easily added or deleted, and spaced as needed in the tankage provided. Further, if scraping of unit areas for biomass determinations was necessary at any time, the flat disc would lend itself better to such use. As a result, the disc material was cut from 1/2 in. (12.7 mm) polystyrene stock at 4 lb/ft^3 density (64 kg/m^3).

Previous disc research had demonstrated that diameters of 0.15 m (6 in.) and 0.3 m (1.0ft) were inadequate to truly distinguish the important factors in disc loading. In these cases the agitation produced at the water surface dominated the results rather than diffusion into or out of the biological film. Thus larger discs were in order.

Two-ft diameter discs (0.6 m) appeared to be the smallest acceptable units, but 4-ft discs (1.2 m) were chosen for several reasons. First, as previously mentioned, when samples are taken continuously at each stage of a six-stage unit and the overall flow is low, there is a substantial alteration of flow and mass of substrate between the first and last stages due merely to the diversion of flow at each stage for samples. Second and more importantly, the rotating elements and the sewage flow would have to be the main source of heat within the pilot plant space in order to resist freezing during winter months. Four-ft units (1.2 m) would involve more flow and the heat provided would be proportionally higher. This later factor was of immense importance at Saline. However, it did not save the unit at Genoa from freezing up.

The use of 4-ft (1.2 m) discs provided an area of 188 m^2 of surface. This area was loaded at rates from 1/4 to 6 $gal/ft^2/day$ (10 $\ell/m^2/day$ to 244 $\ell/m^2/day$). This range of flow loading rates was not anticipated initially. In fact the original plan of testing proposed the highest flow rate at 2.0 $gal/ft^2/day$ (81 $\ell/m^2/day$). This would be for six stages and would therefore be 12 $gal/ft^2/day$ on the first stage. However, at this level of flow nitrification was easily accomplished and it became necessary to go higher and higher in order to cover the full range of bio-activity. Testing had to be terminated however at the 6-gal rate because time was running out. It would have been better to raise the rates to 8 and 10 $gal/ft^2/day$ levels but circumstances would not permit this range of testing.

Figure 5 shows each flow loading tried and the duration of each test. If the testing had proceeded as planned, the 2 gal/ft^2/day test would have been completed by May and subsequent testing would have been carried out during the warm months of the summer and fall with time for checking the results during the winter. As can be seen on Figure 5, the final test for checking purposes was carried out during the worst of the winter weather.

Initial pilot plant design was influenced by prior experiences with the bio-disc in which biological oxidation of organic carbon was studied. Such work indicated that higher efficiencies of removal and narrower ranges for standard deviation of performance were obtained when a fixed area of discs was used in a series mode rather than in parallel. It seemed logical that such a factor could be present in RBS nitrification as well. As a result the pilot plants were constructed in rectangular tanks with one shaft and one drive motor. Six stages were available through the use of movable partitions. Fourteen discs were placed in each stage. But it was expected that 28 discs might be used in each of three stages or 42 discs in each of two stages or 84 discs in one stage if any of these configurations were needed. As soon as the data began to accumulate, it became evident that no time would be available for tests involving the rearrangement of partitions. However the results of such testing could be estimated quite easily from the major data set of the main test series.

Figures D-1 and D-2 in Appendix D show the essential layout of the pilot units. Table D-1 of Appendix D gives the reactor specifications. It should be noted that Figure D-2 shows the sampling port designations. These correspond with the data as tabulated in Appendixes A and B.

SAMPLING

Samples consisted of 3.8-ℓ composites made up of hourly increments, each of 117 ml of test fluid settled for 1/2 hour and placed in a plastic jug containing $HgCl_2$ as a preservative. At the end of the 24-hr test cycle the jugs were picked up and analytical tests were run on each composite. Ammonia, nitrite, nitrate, pH, suspended solids, and COD were run routinely.

The solids accumulated during the half hour setting were accumulated in a drum. These were agitated and sampled for the total suspended solids (sludge) generated by the system. The design of the sampling device is shown in Figure D-3 in Appendix D.

All tests were carried out in accordance with Standard Methods (19) or an approved adaptation for the autoanalyzer (20).

CONSTRUCTION

The tankage was subcontracted to a local welder. The flat discs were no longer available on the market but were still available from scrap. The tanks were trucked to the sites and set up on concrete blocks. Electrical services and plumbing were ditched in alongside existing tanks to provide the necessary heat during the winter to minimize freezing. When all was in place, a shed was built over the entire unit. The shed was insulated, lined with external plywood, roofed, and painted. The flooring consisted of steel grating which was available at the moment. The grating was blocked up about 8 in. above the ground. This permitted spills and leaks without trouble; new hose connections could be made easily and other problems could be simply solved. For example sludge was accumulated in seven drums placed alongside the reactor tank. Each drum was half of a 55-gal steel barrel. After the sludge sample was taken, the barrels had to be drained before the next sample was accumulated. This was accomplished by placing a wooden trough below the grating. Each drum was drained to the trough by pulling a rubber stopper. The trough drained back into the treatment works.

The shaft was set up in the laboratory and the discs carefully glued in place with silicone rubber. A keyway on the shaft assisted in anchoring each disc. Once mounted and dried out, the shaft was trucked to the site and mounted above its tank. After some adjustment of partitions the entire unit was placed in operation.

SECTION 5

EXPERIMENTAL OBSERVATIONS

GENERAL

Initial study of the Saline project suggested that certain portions of the proposed study might result in destruction of the nitrifying flora. If such a circumstance took place during cold weather, it might well be a month or more to reestablish production. Such considerations seemed to demand a back-up unit.

For the above reasons, the 4-ft (1.2 m) pilot unit was set in operation in parallel with a 2-ft (0.6 m) unit which was similar hydraulically. (Several of these 2-ft (0.6 m) units were in existence when this research was envisioned.) A second such 2-ft (0.6 m) unit was set in operation in the laboratory utilizing a synthetic waste and seed from the sewage plant.

Data from the small and large units at the Saline sewage treatment plant appeared to be homogeneous. This was so outstanding that the data for one flow loading test has been taken from the small unit. This became necessary when the large unit broke down. Its nitrifying culture was seriously hurt and data could not be taken for a one-month period. In order to save time the small unit, which continued to operate, was used.

It can be stated here that the laboratory unit never performed like the field units. Every attempt was made to produce similar results. To date it has not been possible to develop total similitude. Items like biomass, ammmnia-N uptake rate, start-up time, continuity of performance, etc., were considerably different between laboratory and field. Such values might be classed as absolute measurements. Relative measurement which seemed to be more nearly correlatible were responses to pH, alkalinity, temperature, dissolved oxygen and presumably toxic effects. Reasons for differences will be discussed in more detail later. Suffice it to say at this point that it would appear that loading values can at present only be obtained through a study of field installations. At Saline, the 0.6- and 1.2-m pilot units were operated continuously during the life of the project for as much loading data as could be gathered.

Unfortunately more time would have been very helpful. The range of testing needed to fully cover the necessary loadings was entirely unexpected. As a result, some of the higher loadings were tested for too short a period to get a true measure of performance.

Through experience it became clear that the fastest way to activate a disc system was to start-up at low flow rates with plenty of seed. When oxidation of the ammonia begins to take place the flow can be increased slowly. It should be noted that the original overall experiment was set up this way. This was fortuitous. The actual experimental design was the result of the feeling that at some point of flow loading the nitrifiers would cease to function, merely because there would not be enough time for them to carry out their oxidation process. As a result the flow was increased slowly so as to reach this point stepwise. It turns out that the organisms can function quite well at extremely high rates of flow. The highest rate attained in this work was 244 ℓ/m^2/day on six stages. This translates to 1464 ℓ/m^2/day on the first stage and still the nitrifiers were oxidizing 20% of the ammonia passing through the stage. The point was never reached where activity ceased.

A total of eleven runs on flow variations were carried out. Table 3 gives the various flows and indicates run numbers and location of data in Appendixes A and B of this report.

EXPERIMENTAL DESIGN

The experimental work originally envisioned involved operating the pilot system first as six stages in series. That configuration was expected to provide the best chance to capture nitrifiers as they passed the unit. Further, many disc systems were known to nitrify well at or below a loading of 1 gal/ft^2/day (40 ℓ/m^2/day). As a result a loading of 0.25 gal/ft^2/day (10 ℓ/m^2/day) was chosen as the best flow for activating the discs. It should be noted that the loading here referred to is the overall loading for the total system (see Table 4). The flow loading at any previously selected point will be found by dividing the total value by the percent of the total area in the system up to that point. Hence if the total flow is 0.25 gal/ft^2/day (10 ℓ/m^2/day) for six stages, the flow for three stages would be 0.5 gal/ft^2/day (20 ℓ/m^2/day), for two stages would be 0.75 gal/ft^2/day (30 ℓ/m^2/day), for one stage would be 1.5 gal/ft^2/day (61 ℓ/m^2/day).

TABLE 3. OUTLINE OF RUNS PERFORMED AT SALINE

Run	Dates	Flow English	Flow Metric	Appendix A data for (NH_3* + N_{ox}†)	Appendix B data for S.S. & C.O.D.
1	8/02/75 10/15/75	1/4 gal/ft^2/day	10 ℓ/m^2/day	A-1	B-1
2	10/17/75 11/07/75	1/2 gal/ft^2/day	20 ℓ/m^2/day	A-2	B-2
3	11/19/75 2/06/76	1.0 gal/ft^2/day	40 ℓ/m^2/day	A-3	B-3
4	2/09/76 3/03/76	1.5 gal/ft^2/day	61 ℓ/m^2/day	A-4	B-4
5	3/10/76 5/03/76	2.0 gal/ft^2/day	81 ℓ/m^2/day	A-5	B-5
6	5/10/76 6/07/76	2.5 gal/ft^2/day	101 ℓ/m^2/day	A-6	B-6
7	6/16/76 7/21/76	3.0 gal/ft^2/day	122 ℓ/m^2/day	A-7	B-7
8	7/30/76 8/25/76	4.0 gal/ft^2/day	162 ℓ/m^2/day	A-8	B-8
9	9/03/76 9/15/76	5.0 gal/ft^2/day	203 ℓ/m^2/day	A-9	B-9
10	9/17/76 11/01/76	6.0 gal/ft^2/day	244 ℓ/m^2/day	A-10	B-10
11	11/22/76 2/05/77	3.5 gal/ft^2/day	142 ℓ/m^2/day	A-11	B-11

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of (NO_3 + NO_2) mg/ℓ as N.

TABLE 4. SURFACE DISTRIBUTION AND FLOW LOADING TO STAGES

Stage	Incremental area (ft^2) or m^2	Percent of total	Incremental flow loading $(gal/ft^2/day)$ or $\ell/m^2/day$
1	(337) 31 m^2	17	(1.50) 61
2	(674) 62 m^2	33	(0.75) 30
3	(1011) 93 m^2	50	(0.50) 20
4	(1348) 124 m^2	67	(0.37) 15
5	(1685) 155 m^2	83	(0.30) 12
6	(2022) 186 m^2	100	(0.25) 10

When a complete range of flow values is tested it becomes possible to factor out the influence of staging. Reference to Table 6 shows for example a loading of 3.0 gal/ ft^2/day which appears at the locations circled. These points may be enumerated as follows (see Table 5):

TABLE 5. DATA LOCATION (3 gpd/ft^2 loading)

Stage	$(gal/ft^2/day)$ Loading	Data table
1	(3.0) 122 $\ell/m^2/day$	A-2
2	(3.0) 122 $\ell/m^2/day$	A-3
3	(3.0) 122 $\ell/m^2/day$	A-4
4	(3.0) 122 $\ell/m^2/day$	A-5
5	(3.0) 122 $\ell/m^2/day$	A-6
6	(3.0) 122 $\ell/m^2/day$	A-7

Further examination of the tabulated data should establish the removal efficiency associated with a constant flow loading and a varying number of stages.

This experimental design also provides a means for determining the dispersion of values from which a prediction is made and a visual concept defining ultimate quality for a given environmental condition.

TABLE 6. DESIGN OF OVERALL EXPERIMENT

		Flow gal/ft^2/day* (to the point)										
Stage	Factor	A-1[†]	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	A-10	A-11
1	6.0	1.5	$\boxed{3.0}$	6.0	9.0	12.0	15.0	18.0	24.0	30.0	36.0	21.0
2	3.0	0.75	1.5	$\boxed{3.0}$	4.5	6.0	7.5	9.0	12.0	15.0	18.0	10.5
3	2.0	0.50	1.0	2.0	$\boxed{3.0}$	4.0	5.0	6.0	8.0	10.0	12.0	7.0
4	1.5	0.37	0.75	1.5	2.25	$\boxed{3.0}$	3.7	4.5	6.0	7.5	9.0	5.2
5	1.2	0.30	0.60	1.2	1.8	2.4	$\boxed{3.0}$	3.6	4.8	6.0	7.2	4.2
6	1.0	0.25	0.50	1.0	1.5	2.0	2.5	$\boxed{3.0}$	4.0	5.0	6.0	3.5

*Multiply all terms by 40.7 to yield metric equivalents.

[†] Tables A-1 through A-11 will be found in Appendix A.

FLOW LOADING AS AFFECTING NITRIFICATION

Construction, testing and correction of miscellaneous problems required about 6-1/2 months. Operational testing began on August 1, 1975. Actual start-up had taken place on July 23. Spot checks were taken to note the disc activation time.

Date	Influent NH_3-N	Effluent NH_3-N
7/23	10.3 mg/ℓ	10.3 (start-up)
7/29	7.5 mg/ℓ	3.5 mg/ℓ
7/31	8.0 mg/ℓ	1.0 mg/ℓ
8/01	9.5 mg/ℓ	0 mg/ℓ

Apparently about nine days were required to activate the new disc system at the first loading selected 0.25 gal/ft^2/day (10 ℓ/m^2/day).

This run will be referred to as run 1 and its data is reported in Tables A-1 and B-1 of respective appendixes. It was important to have a grasp of the performance and operating characteristics of the disc system, so the run was continued from 8/02 through 10/15. Nineteen sampling days were covered. Flow was set each day of adjustment by a valve on the discharge side of the submersible pump. It was felt that with the head loss constant on the system and the high quality of the effluent being fed to the pilot plant, such control was adequate. Experience with the system revealed that a certain amount of plugging of the valve took place. Low flow settings were hard to hold but higher flows were easier to control. Each day the flow was measured volumetrically when samples were picked up. This flow is recorded in column 2 of Table A-1 in Appendix A. The flow was then adjusted to the correct value noted as the "flow loading." Actual flows through the unit reflect a variation between these two extreme values.

Examination of Table A-1 in Appendix A shows the characteristics of the data accumulated. For example stage 1 was removing 70% of the influent ammonia leaving only 30% for the remaining five stages. Even so, readings of less than 0.4 mg/ℓ NH_3 were seldom if ever reached in the effluent.

Further, anomalies were frequently encountered. For example on August 26 influent ammonia was 14.4 mg/ℓ while the effluent of stage 1 was 1.9 mg/ℓ for 87% removal. On October 1 the influent ammonia was 14.4 mg/ℓ while the first stage effluent was 0.8 mg/ℓ for a 94% removal. At the next sampling period the influent ammonia was 13.2 mg/ℓ and the effluent 13.5 for a zero percent removal on stage 1 but the effluent of stage 2 was 0.2 mg/ℓ for a 98% removal over two stages.

At first it might be assumed that something toxic to nitrifiers might have been tributary to the Saline plant. However, whatever it was had no effect on stage 2 and if the oxidized nitrogen fraction of stage 1 influent is examined, it is found to be exceptionally high at 7.5 mg/ℓ. Obviously, no toxic ingredient had affected the trickling filters. Regardless of the cause of the problem it can be stated with certainty that the effluent of a single stage is highly variable even when lightly loaded. The effluent of the second stage however is much more uniform and the trend is continuous with further stages (depending on the loading).

The following data are taken directly from Table A-1 and reflect the average of 19 values from each stage.

NH_3-N

	Influent	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
$\bar{x}$	13.4	4.1	0.7	0.5	0.4	0.4	0.4
σ	2.6	6.1	0.4	0.4	0.3	0.2	0.2

Since stage 1 seemed to be doing most of the work, the flow was doubled to 0.5 gal/ft^2/day (20 ℓ/m^2/day). Again much the same pattern prevailed. The anomaly previously noted, namely, the large drop in efficiency detected in stage 1 was again apparent on 10/17 and 10/20. The additional flow still did not provide sufficient substrate to load the unit and the last three stages had little ammonia oxidation to carry forward.

Again the flow was doubled to 1.0 gal/ft^2/day (40 ℓ/m^2/day). This gave a 6 gal/ft^2/day (244 ℓ/m^2/day) rate over stage 1 and was assumed to be a critical loading at least for the first four stages. The peviously noted anomalies occurred again especially during January. However, the second, third, and fourth stages made up for any deficiencies which developed in stage 1 and even on January 26 when stage 2 had an 11.2 mg/ℓ influent and 11.4 mg/ℓ effluent, the effluent of stage 6 was a respectable 1.4 mg/ℓ. It is important to note that these anomalies will distort stage averages unless a substantial amount of data is compiled.

While the testing to this time seemed to give an acceptable average of 0.5 mg/ℓ on the fourth stage, there was no way to tell how much more load the system might be able to take.

The flow was therefore raised to 1.5 gal/ft^2/day (61 ℓ/m^2/day) and then to 2.0, 2.5, and 3.0. At this higher flow, the anomalies previously noted began to work their way through the system. For example, on June 21 stage 1 had an ammonia influent of 21.5 mg/ℓ and an effluent of 20.8 mg/ℓ. Stage 2 had an effluent of 17.3 mg/ℓ and stage 6 an effluent of 5.0 mg/ℓ. Since the series of tests had an average effluent at stage 6 of 0.7 mg/ℓ, it appeared that the nitrifiers throughout the disc series were sick. Certainly an effluent of 5.0 mg/ℓ is almost 10 times higher than might be expected. Out of eleven test values observed in this series, three exceeded 1.0 mg/ℓ because of such upsets.

When the overall flow was raised to 4.0 gal/ft^2/day (162 l/m^2/day), seven out of ten values exceeded 1.0 mg/ℓ of ammonia at stage 6.

Time was becoming critical at this point. So after a poor run at 5.0 gal/ft^2/day (203 ℓ/m^2/day), the flow was raised to 6.0 gal/ft^2/day (244 ℓ/m^2/day) overall. This corresponds to 36 gal/ft^2/day (1464 ℓ/m^2/day) on stage 1 and was considered to be an extremely high loading level. Even so results show that 50% of the observed values of effluent ammonia at stage 6 were still below 2.0 mg/ℓ.

Figure 7 shows the average ammonia removals per stage for the major loading levels. Unfortunately, the sinusoidal temperature variations affect these results and the ammonia concentrations tributary to the pilot unit likewise affect the biomass.

Figure 8 is an attempt to normalize the varying ammonia levels at the pilot plant influent. This gives a valuable set of curves indicating the effect of staging and overall flow loading values involved in producing a given percent removal. It should be remembered that these values are taken from averages and that runs are more or less a month long.

Since the nitrifiers were not loaded beyond the 36 gal/ft^2/day (1464 ℓ/m^2/day) loading, it cannot be stated with certainty what the effect of higher loadings would be. However, it seems logical that these results may be extended a moderate amount if needed. For example, in Figure 8, it would be possible to extend the 6 gal (244 ℓ) loading value to seven or eight stages if it were necessary to reduce the effluent to about 10% ammonia nitrogen remaining (90% removal).

More than six stages at flow loading values less than 3 gal/ft^2/day 122 ℓ/m^2/day) would seem to be counterproductive because of the low rate of NH_3-N removal beyond the fifth stage. Suffice it to say that Figure 8 seems to afford the best technique available to relate stages, overall flow loading and efficiency of removal. With this nest of curves, it is possible to set for 90% removal and to decide on the overall flow loading and the number of stages desirable to achieve the desired level of removal.

In the reactor tank as tested, stage 1 has a capacity of 54.7 gal (206 ℓ), and at the highest flow rate used had a detention time of 6.5 min.

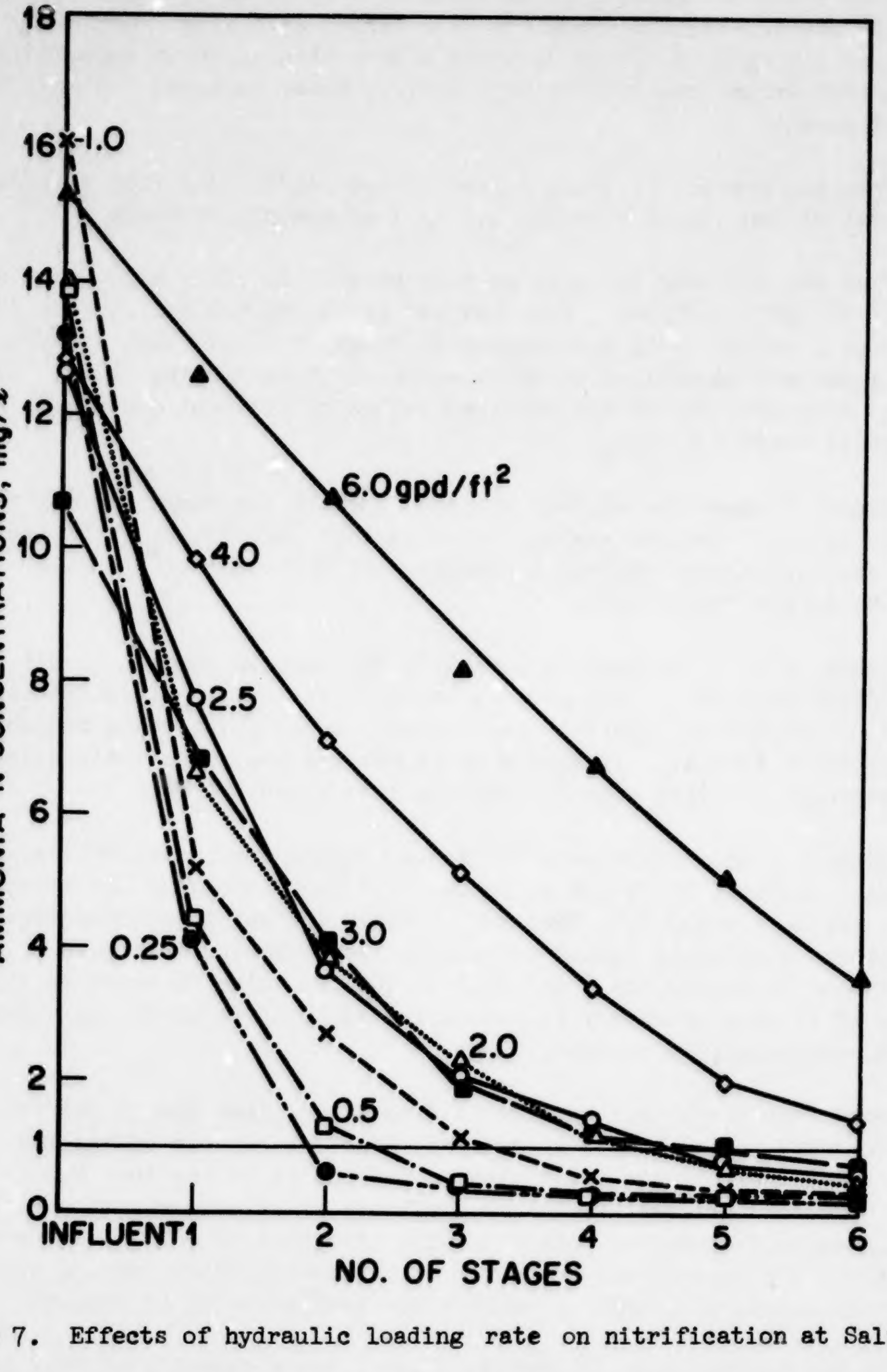

Figure 7. Effects of hydraulic loading rate on nitrification at Saline.

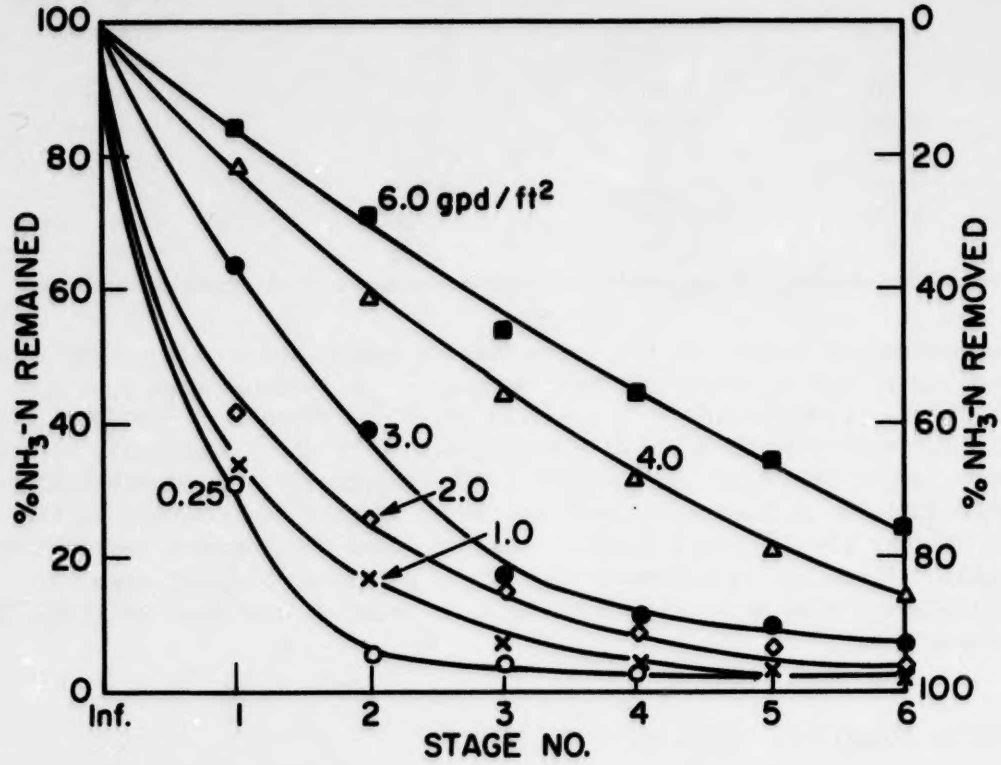

Figure 8. Ammonia removal normalized with regard to influent concentrations.

The detentions at other flow rates and the corresponding weights of nitrogen oxidized in stage 1 are shown in Table 7.

TABLE 7. FLOW VERSUS TIME AND NITROGEN OXIDIZED IN STAGE 1

Overall hydraulic load, gal/ft^2/day	Influent flow, gpm	Stage 1 Detention time, min	Stage 1 lb N oxidized, per 1000 ft^2/day
0.25	0.35	156	0.11
0.50	0.70	78	0.24
1.00	1.41	39	0.55
2.00	2.81	19.5	0.79
3.00	4.22	12.9	0.58
4.00	5.62	9.8	0.54
5.00	7.02	7.8	0.37
6.00	8.43	6.5	0.72

Neglecting the lowest two hydraulic loading values above (since they represent underloading), the N oxidized values of the loadings from 1 to 6 gal/ft^2/day average 0.60 lb N oxidized per 1000 ft^2/day (3 kg/m^2/day). The time for this oxidation varied from 6.5 min to 39 min. Apparently within these limits detention time is relatively unimportant. It should also be noted that the maximum ammonia-N removal on stage 1 is developed at the 2 gal/ft^2/day (80 ℓ/m^2/day) loading value and does not increase beyond that level. If removal is a direct function of nitrifier biomass, then the variable too must have reached its maximum level at that same critical flow loading level.

AMMONIA LOADING AS AFFECTING NITRIFICATION

Reference to Table 7 shows that the consumption of ammonia by the nitrifiers increased up to a level of about 0.6 to 0.7 lb of ammonia as N, per 1000 ft^2 of disc area in stage 1. Beyond that point no additional ammonia was consumed by the micro-flora inhabiting stage 1. At the point when this level of nitrogen was tributary to stage 1 the flow to the six-stage pilot unit was 1 gal/ft^2/day overall and the flow passing stage 1 was 6 gal/ft^2/day. Table 7 indicates that a 600% increase inflow had no further effect on this stage.

Examination of the total data package Tables A-1 to A-11 (Appendix A) indicates that each stage of discs comes up to a similar removal level and then passes any residual ammonia to the next stage of discs. Apparently this level of removal requires a fixed area of support for the biomass which is unaffected by flow, turbulence or end-products at least within the range of testing covered in this work.

Figure 9 is a plot of the actual data for the work performed. It merely shows ammonia applied in pounds and ammonia removed in pounds per day for the system used. Each stage being 337 ft^2 (31.6 m^2) or 0.34 of 1000 ft^2, the graph could be altered by dividing each value by 0.34 which would put the units in thousands of square feet. Similarly the graphs could be converted to metric equivalents.

Without question the overall figure shows each stage taking its fixed level of ammonia and no more. Further the line O-A defines the asymptote toward which the series of stages trend as the flow increases and the number of stages increases. The slope of O-A is 0.95/1.00 showing that if a design requiring a fixed area of discs is laid out with a sufficient number of stages, 95% removal can be obtained.

The curves look so uniform that they might well be restructured to add more and yet more stages and higher and higher flows. Logic dictates however that there must be a limit at some point. Here, experience must be depended upon for guidance.

It had been hoped that the Saline unit could have been driven past such a point of critical loading. When the EPA indicated that no extension could be given to the work, it was decided to stress a laboratory pilot unit past the critical point.

It has been established that anomalies become more and more frequent as the flow increases. A severe anomaly may seriously affect the entire unit for a day or two. In the case of the laboratory unit and at the higher flow values the unit does not come back easily or in some cases at all. In the field, the unit seems to respond beautifully to an anomaly. A few bad samples may be produced but then the pilot plant returned to high efficiency operation. Such work therefore had to be done in the field, or else remain uncompleted.

STAGING

The flow loading, mass loading, and staging effects are so interrelated in this work that a separate section on staging may seem slightly redundant. However, staging effects should be stressed for purposes of adequate design. As a result the following is offered.

If Table 6 (page 28) is expanded to include the results of the

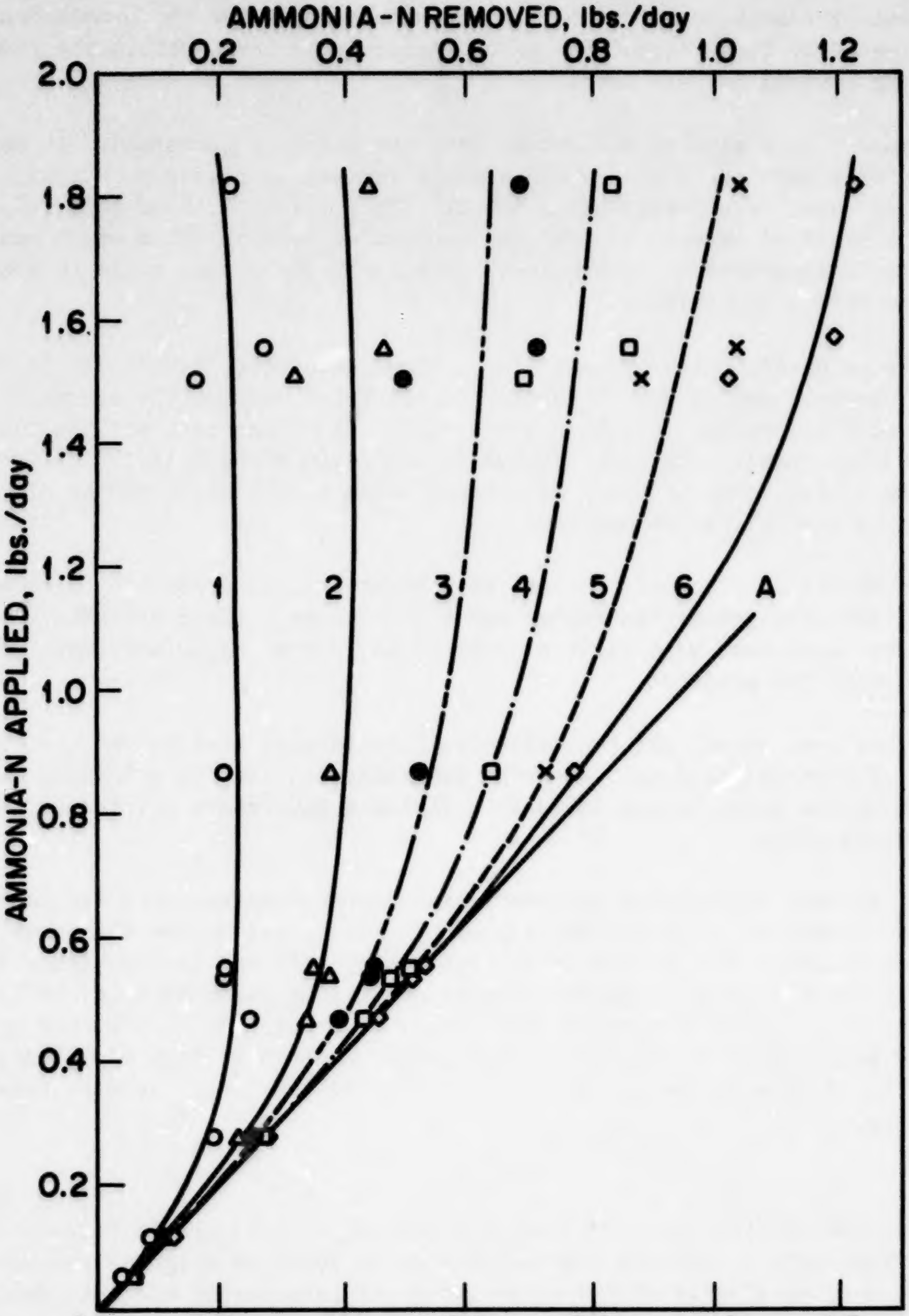

Figure 9. Mass loading and removal at Saline.

tabulated data in Appendix A, Table 8 is the result.

TABLE 8. EFFECT OF STAGING ON NH_3-N REMOVAL FOR CONSTANT FLOW ($3\ gpd/ft^2$ loading)

Stage	Loading gpd/ft^2	Source of data Appendix A Table No.	NH_3-N percent removed	Standard deviation mg/ℓ
1	3.0	A-2	70%	4.7
2	3.0	A-3	74%	2.9
3	3.0	A-4	93%	0.6
4	3.0	A-5	91%	0.6
5	3.0	A-6	94%	0.5
6	3.0	A-7	93%	0.1

Obviously if a 3.0 $gal/ft^2/day$ (122 $\ell/m^2/day$) flow loading is chosen for design purposes, the disc area should be arranged in three stages or more. The results as shown above indicate a 23% improvement for three stages over a single stage. The most important factor however would be the effect on the standard deviation of the mean. This term in essence would define the accuracy with which the defined average must be associated. Virtual certainty (95% assurance) would lie within $\pm 2\ \sigma$ of the mean value.

Examination of the 6.0 $gal/ft^2/day$ (244 $\ell/m^2/day$) flow loading shows a very similar trend. In essence the first and second stages show erratic results. Three or more stages produce increasingly reliable results. When all loadings are considered and placed on a chart relating hydraulic loading per stage and percent ammonia nitrogen removed, Figure 10 results. Only loadings from 1/4-12 gpd/ft^2 (10.2-488 $\ell/m^2/day$) are shown in Figure 10 since removals at higher flows fall below the 60% removal level.

Figure 10 indicates wide divergence for the first and second stages as noted above. However, the third through sixth stages form an s-shaped curve which crosses the critical percent removal levels at well defined flow loading points. For example the following seem to be clearly indicated.

1. Three stages generate a somewhat erratic performance above 90% removal. As a result, for a value such as 95% removal, the recommendation would be for four or more stages and for flow loadings of 2 to 2.5 gpd/ft^2 (81 to 102 $\ell/m^2/day$).

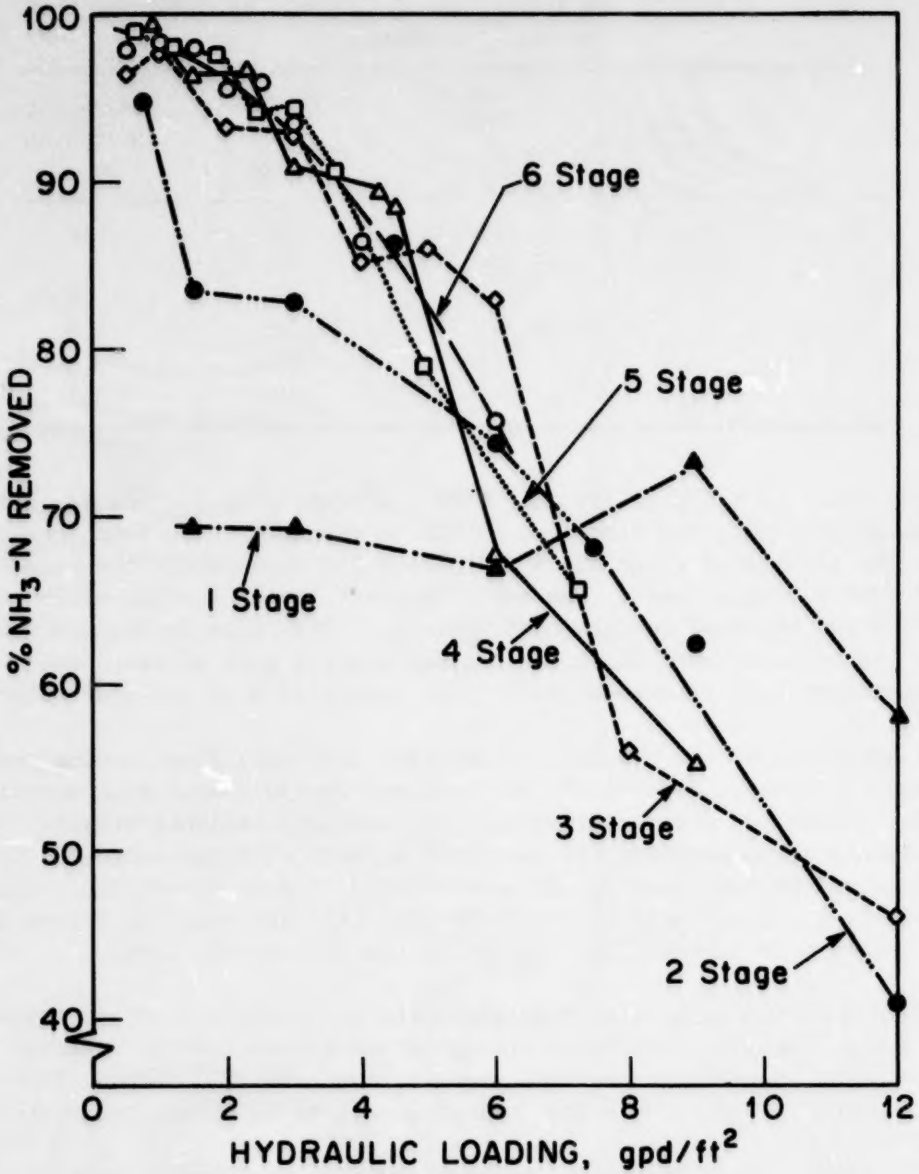

Figure 10. Stage loading versus NH_3-N removal efficiency.

2. For 90% removal. the recommendation would be for 3.5 to 4.0 gpd/ft^2 (143 to 163 ℓ/m^2/day) and four to six stages.

3. For 85% removal, the recommendation would be for 4.5 to 5.5 gpd/ft^2 (183 to 244 ℓ/m^2/day) and four to six stages.

It should be emphasized that the lower values in the range of flow loading represent a conservative approach while the higher values in the range are a more liberal approach. Table 9 defines the limits of the experimental work for the three levels of 85, 90, and 95% ammonia-nitrogen removal.

It must be remembered that these observations apply to secondary effluent, well seeded and where ammonia-nitrogen levels will vary from 10 to 22 mg/ℓ with an average of 16 mg/ℓ.

NITRIFICATION AS AFFECTED BY pH AND ALKALINITY

The pH of the culture medium has been shown to affect the rate of growth of both Nitrosomonas and Nitrobacter in pure and mixed cultures. It should be remembered that Schoesing and Muntz (2) as previous noted on page 3, used crushed calcium carbonate in order to neutralize the acids generated by nitrifiers. These acids are actually the waste products of the organisms involved and it is logical that they will become toxic at some finite concentration level. Alkaline substances are therefore necessary to insure that the acids will be neutralized and held at a low level in the vicinity of the organisms.

Table 10 summarizes the reported values for optimal pH as noted in the literature.

In the present research, observations of acid concentration soon revealed the fact that acceptable pH conditions would prevail during nitrification and that no adverse acid impact would be generated.

Inspection of Table 11 indicates that over a wide range of flow values, no regular change in pH values was discernible in the recorded data. All observations seemed to fit the optimum range for attached growth as defined by Srna and Baggaley (21).

There was a drop in alkalinity apparent with increasing nitrification but it lacked a well defined trend. Within a run the alkalinity dropped from stage to stage but between runs observed changes were not uniform.

Since the Saline pilot unit flow was large and facilities were not

TABLE 9. FINAL EXPERIMENTAL RESULTS

		Flow gal/ft^2/day* (to the point)										
Stage	Factor	A-1†	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	A-10	A-11
1	6.0	1.5	3.0	6.0	9.0	12.0	15.0	18.0	24.0	30.0	36.0	21.0
2	3.0	9.75	1.5	3.0	4.5	6.0	7.5	9.0	12.0	15.0	18.0	10.5
3	2.0	0.50	1.0	2.0	3.0	4.0	5.0	6.0	8.0	10.0	12.0	7.0
4	1.5	0.37	0.75	1.5	2.25	3.0	3.7	4.5	6.0	7.5	9.0	5.2
5	1.2	0.30	0.60	1.2	1.8	2.4	3.0	3.6	4.8	6.0	7.2	4.2
5	1.0	0.25	0.50	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	3.5
		95% removal										
		90% removal										
		85% removal										

*Multiply all terms by 40.7 to yield metric equivalents.

†Tables A-1 through A-11 will be found in Appendix A.

TABLE 10. REPORTED OPTIMAL pH VALUES FOR NITRIFICATION

Authors	Organisms	Optimal pH range	Date
Meyerhoff (21)	Nitrosomonas - pure culture	8.5 - 8.8	1917
Hoffman & Lees (22)	Nitrosomonas - pure culture	8.0 - 9.0	1953
Engel & Alexander (23)	Nitrosomonas - pure culture	7.2 - 9.0	1960
Loveless & Painter (24)	Nitrosomonas - pure culture	7.5 - 8.0	1968
Buswell, *et al*. (25)	Nitrosomonas - pure culture	8.0 - 8.5	1954
Lees (26)	Nitrobacter - pure culture	7.2 - 8.2	1954
Meyerhoff (21)	Nitrobacter - pure culture	8.5 - 9.0	1917
Boon & Laudelot (27)	Nitrobacter - pure culture	7.0 - 8.6	1962
Wild, Sawyer & McMahon (28)	Mixed Culture - Activated Sludge	8.4	1971
Downing, *et al*. (29)	Mixed Culture - Activated Sludge	7.2 - 8.0	1966
Huang & Hopson (30)	Mixed Culture - Attached Growth	8.5	1974
Srna & Baggaley (21)	Mixed Culture - Attached Growth	7.0 - 8.2	1975

TABLE 11. TYPICAL pH AND ALKALINITY VALUES DURING NITRIFICATION AT SALINE

Flow load ℓ/m^2/day	Date	Sampling point						
		S_1	S_2	S_3	S_4	S_5	S_6	S_7
10	8/12/75 pH	-	7.4	7.8	7.9	8.0	7.9	8.1
41	12/31/75 pH	-	7.7	7.8	7.9	8.2	8.1	8.0
	Alk*	-	142	130	130	124	112	93
163	8/25/76 pH	7.4	7.4	7.5	7.4	7.4	7.3	7.3
	Alk	237	232	212	202	197	182	177
203	9/15/76 pH	7.3	7.3	7.3	7.2	7.3	7.4	7.2
	Alk	285	280	276	266	254	248	232
142	12/31/76 pH	7.4	7.1	7.2	7.1	7.2	7.1	7.2
	Alk	192	184	176	152	140	124	84

provided for systematic pH adjustment in the field, it was evident that any work on the subject of pH would have to be carried out in the laboratory.

As a result, a six-stage laboratory unit, 2 ft (0.61 m) in diameter was evaluated at eleven levels of alkalinity. The influent ammonia-nitrogen was set at 20 mg/ℓ and analyses were run on the plant effluent. Figure 11 shows the values of ammonia-nitrogen at each stage as well as the effect of nitrification on the respective effluent levels of alkalinity. Figure 12 indicates that the rate of usage of alkalinity closely approximates 7 mg/ℓ per mg/ℓ of ammonia-nitrogen oxidized.

Figure 13 relates the coefficient of pH dependence (K_{pH}) to the same coefficient at pH 7.5 ($K_{7.5}$). The relationship suggests that nitrification ceases at pH 6.0. This observation must be tempered by the concept of short-term change as contrasted to long-term change. In the latter case, acclimation has taken place. The response of such a culture may appear to generate an exception to the pattern defined in Figure 13. In actuality, long-term and short-term responses are two distinct responses to an environmental condition. Both are a normal pattern of development in nitrification. Long-term change is much more difficult to establish and in waste treatment, may well require conditions that would be difficult to establish for a long enough period to develop the necessary flora. Haug and McCarty (22) developed a nitrifying culture at pH 6.0 that functioned to produce complete oxidation after 10 days in their submerged filter. This must be considered a long-term response in contrast to the suggestion of zero nitrification predicted by Figure 13 as a short-term response.

EFFECT OF TEMPERATURE ON NITRIFICATION

The optimum temperature for nitrification reported in the literature varies considerably. Buswell (25) cites 30°-36°C as optimum for Nitrosomonas. Laudelot and Van Tichelen (23) report 42°C as an optimum for Nitrobacter while Painter (24) found that 34°-35°C was best for the same organism. Little or no growth was experienced below 5°C and above 45°C for both Nitrosomonas and for Nitrobacter. Gibbs (35) reported that 53°-55°C inactivated nitrifiers. Sawyer and Bradney (26) used pasteurization at 55°C for inactivation of nitrifiers in BOD work which has proven to be very effective. The Technology Transfer publication on Nitrogen Control (37) implies that attached cultures can withstand cold temperatures considerably better than suspended cultures. There is still some inconsistency in the literature regarding temperature effects and it was hoped that this research would help clarify the situation.

The field units at Saline were set up in a temporary frame building in which a row of plywood windows could be opened for easy access in removing

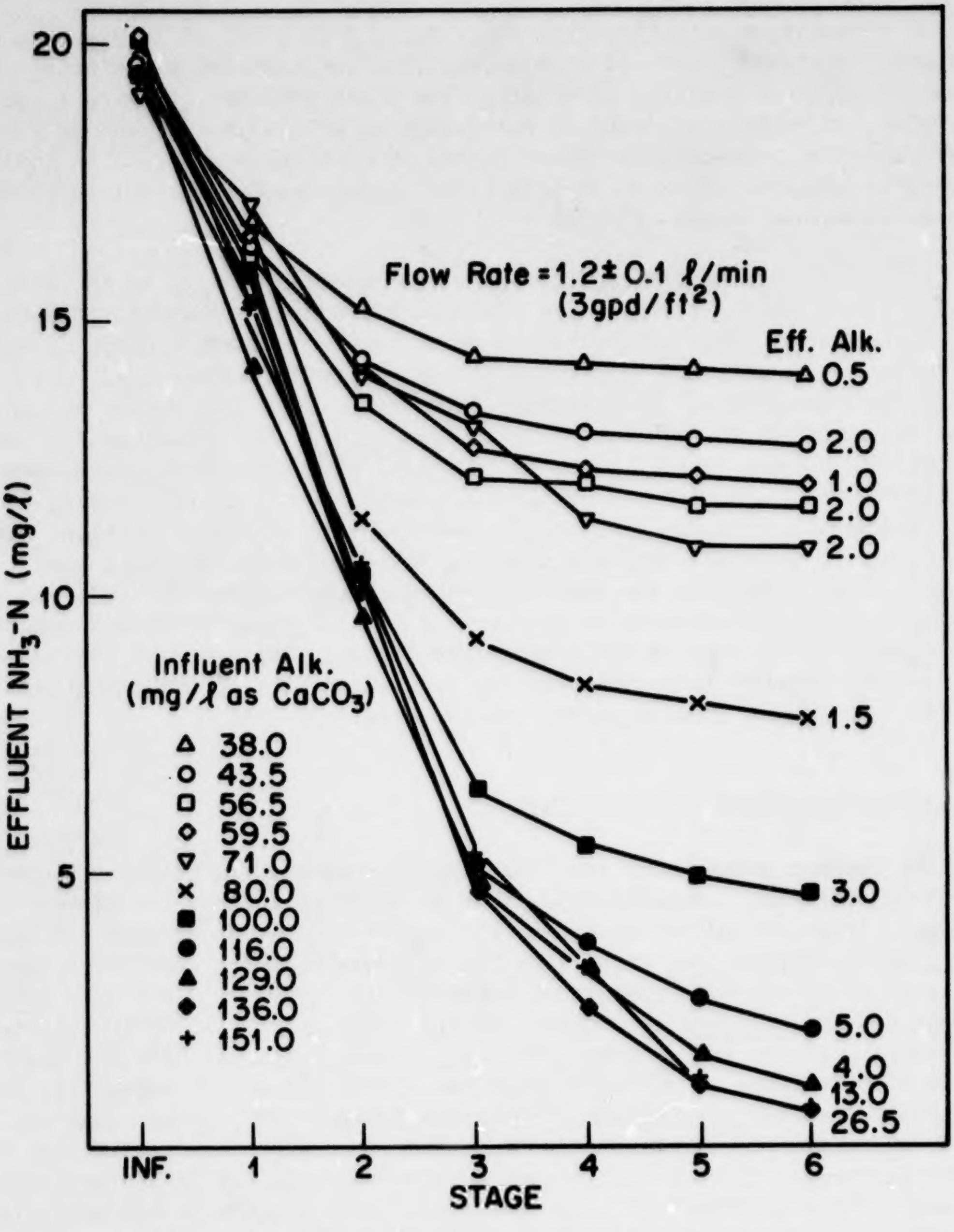

Figure 11. Effect of alkalinity on nitrification.

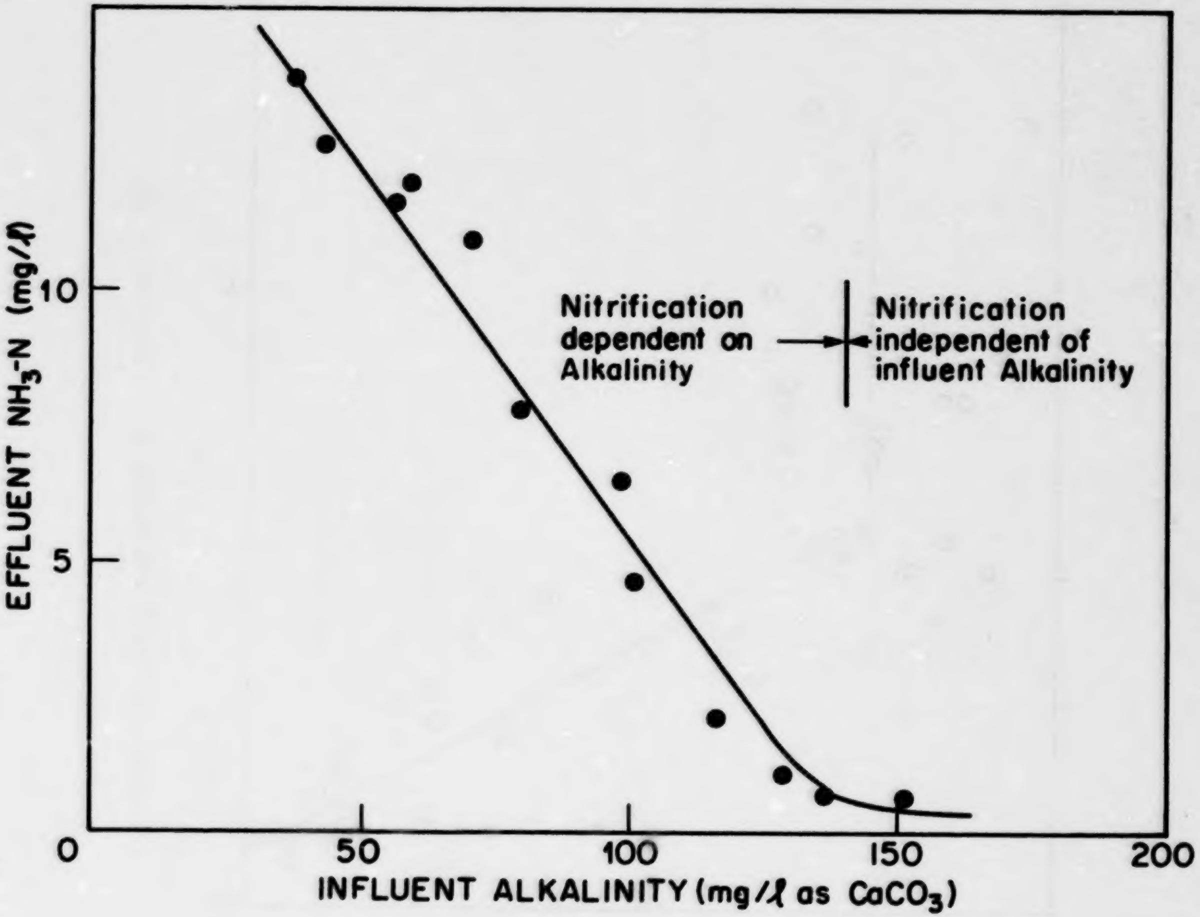

Figure 12. NH_3-N oxidation as a function of alkalinity.

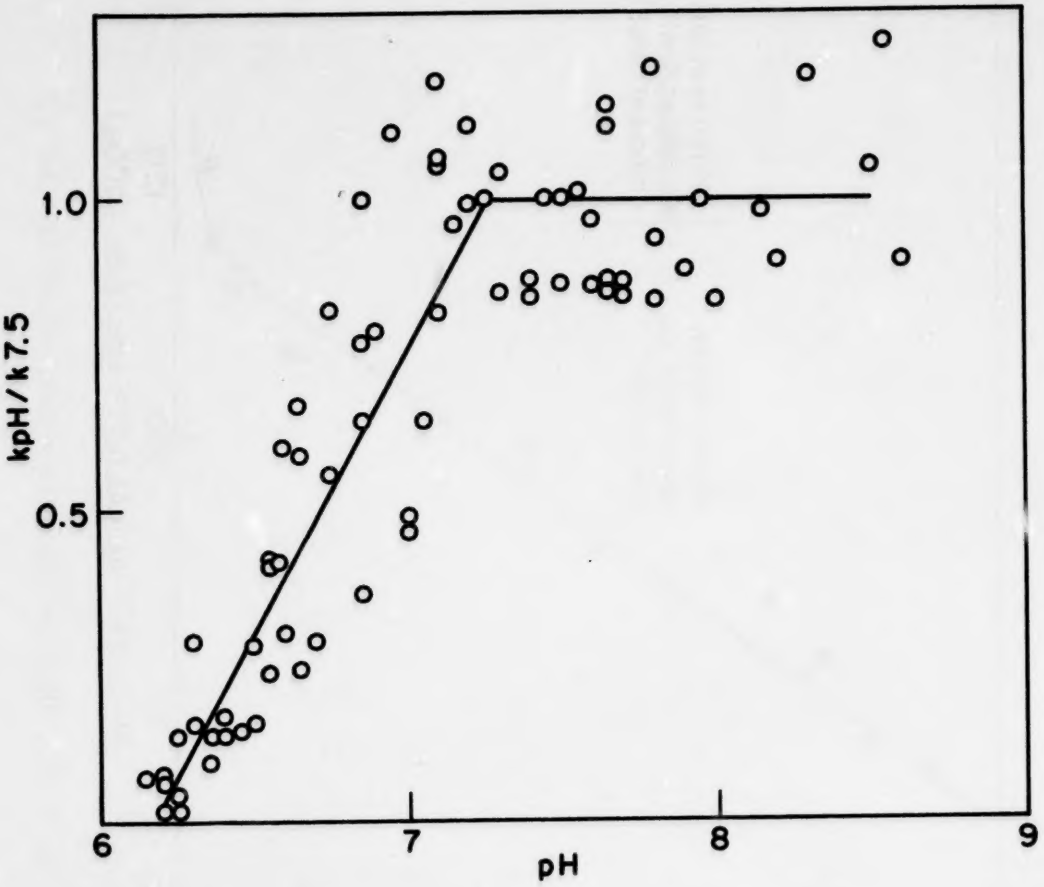

Figure 13. NH_3-N oxidation as a function of pH.

the discs. The major source of heat for the entire operation was the warm sewage flowing over the discs. When the windows were tightly closed the interior temperature fell to a low of 9°C. It was thought that opening the windows by degrees during the coldest winter months would slowly depress the temperature and enable observations to be made below 9°C.

The 2-ft (0.61 m) unit held less heat and was placed somewhat lower in the room than its 4-ft (1.2 m) counterpart. It was frozen solid when no effect was apparent on the 4-ft (1.2 m) unit. As the ice formed and the discs rotated, the biomass was neatly stripped from the disc surfaces. The 2-ft (0.61 m) unit had to be abandoned.

Further work with the 4-ft (1.2 m) unit showed the futility of the total approach. The air temperature at one point outside was 12°C below zero, directly over the 4-ft (1.2 m) unit it was 2°C below zero and the reactor fluid was 6° to 7°C. Thus the biomass was circulating in the air at -2°C with gusts to -12°C and the environment in the liquid phase was at +7°C. This condition was not one in which good temperature work could be performed. The date on which this occurred was December 1, 1976 and again on December 13 and 14. Table A-11 in Appendix A shows the effect on the nitrification process. Effluent ammonia-N increased from 0.8 mg/ℓ to 12.9 mg/ℓ. The window was closed the next day with an immediate improvement. The process did not appear to be harmed by the contact with such cold air. Another similar experience on December 13 and 14, 1976 produced a similar result. Again it appeared that a laboratory study would be the best approach to the problem. The design of the laboratory equipment involved six stages of 2-ft (0.61 m) reactors and a synthetic feed. Laboratory cooling equipment could be used to moderate the temperatures in the liquid phase, but no controlled environmental room was available to prevent some warming up of the six-stage reactor (especially at 2°C level). As a result it was decided to proceed with a gradient of temperature through the reactors. The responses obtained at the different temperatures are shown in Figure 14. Figure 15 is an attempt to normalize the data for a series of single temperature values rather than the use of ranges. The result is a useful set of curves. Figure 16 is a locus of points reflecting the ratio of the reaction coefficient at any temperature T to the coefficient at 20°C, plotted against temperature. K is defined as mg of ammonia-N removed per mg of biomass per hour. The resulting values appear to define a steadily increasing rate of nitrification from 2°C to 30°C. This relationship too must be characterized as a short-term response.

Probably the 4-ft (1.2 m) reactor at Saline was more nearly performing in a long-term response mode. As a result, data taken from it were not expected to correlate with the laboratory work. Results at Saline were divided into sets covering temperatures (6-8)°C, (8-10)°C, (10-12)°C, and (12-13)°C. Reaction rates for similar temperature ranges as observed in the laboratory work can be computed from Figure 16 and adjusted to 1.0 at 12.5°C. The

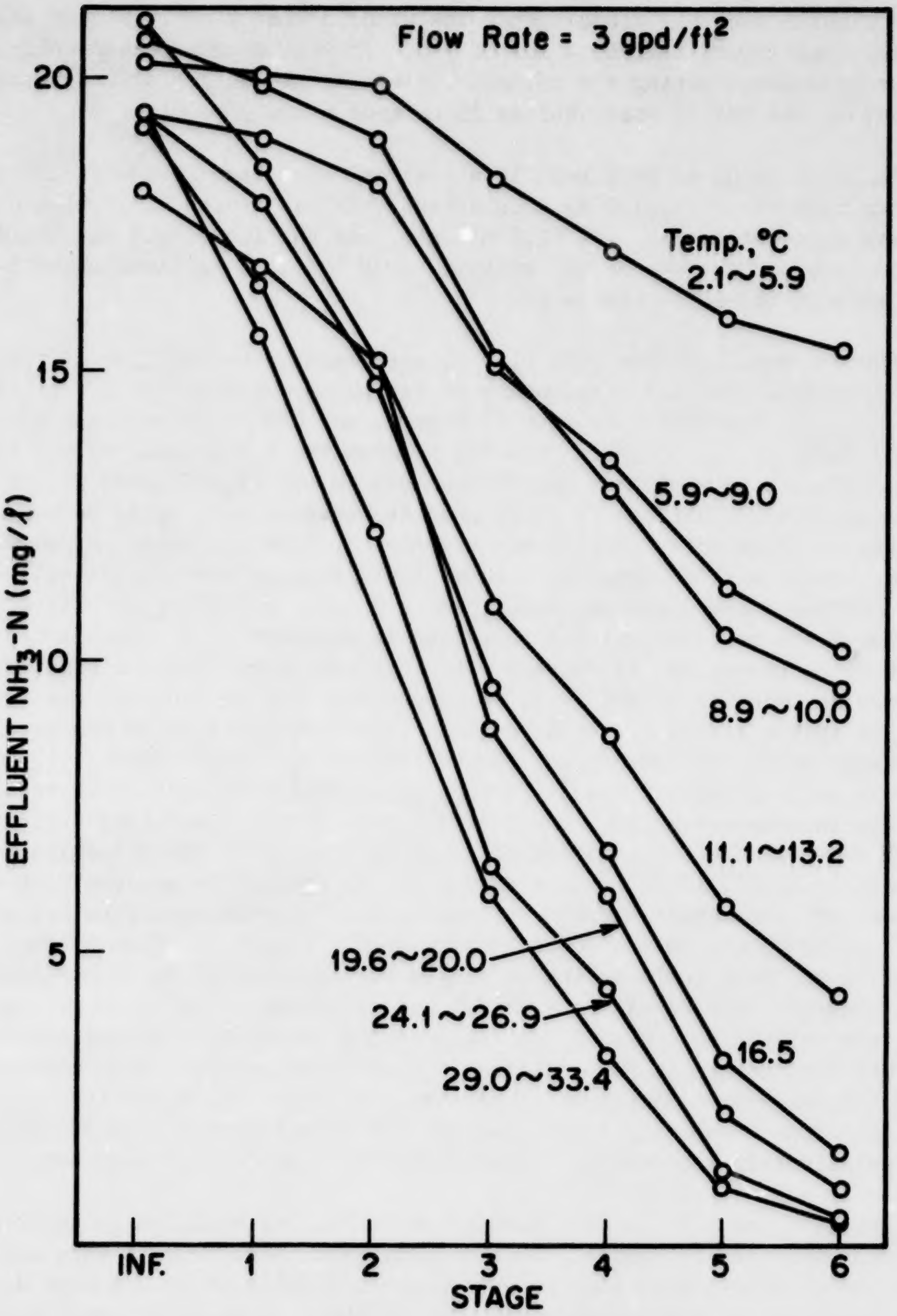

Figure 14. Laboratory temperature study.

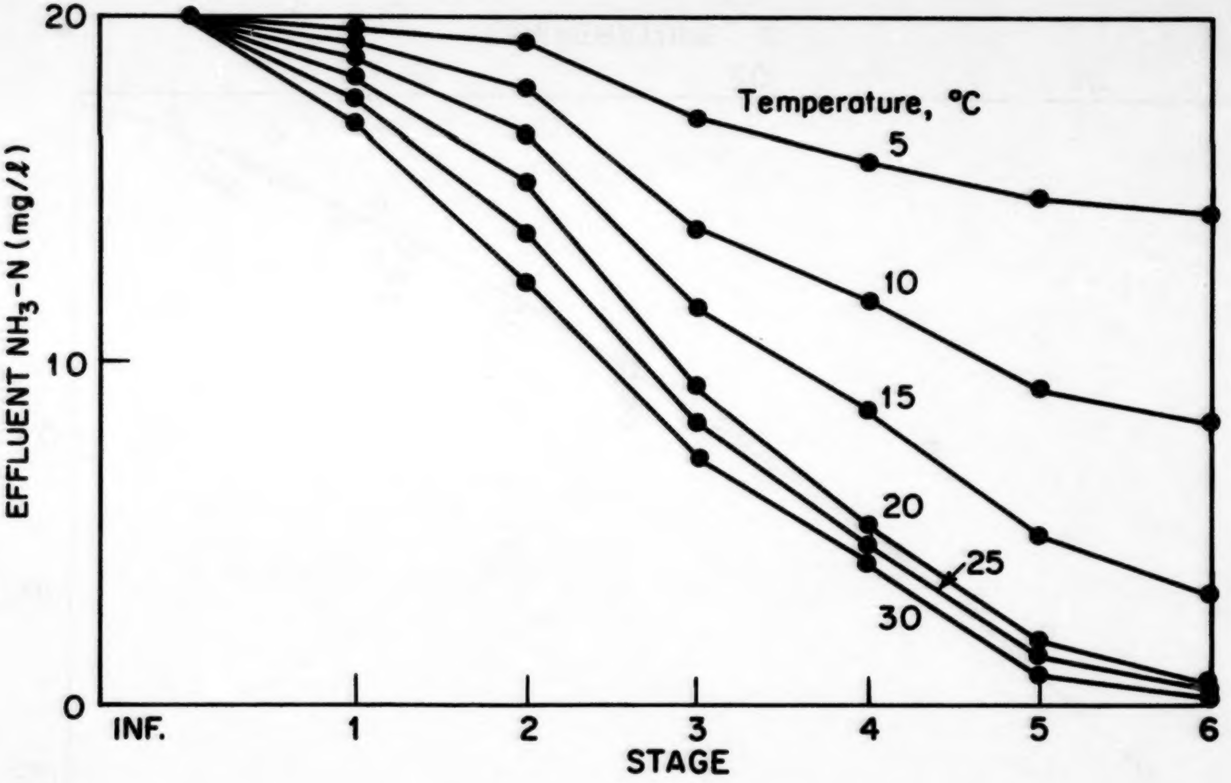

Figure 15. Normalized temperature data.

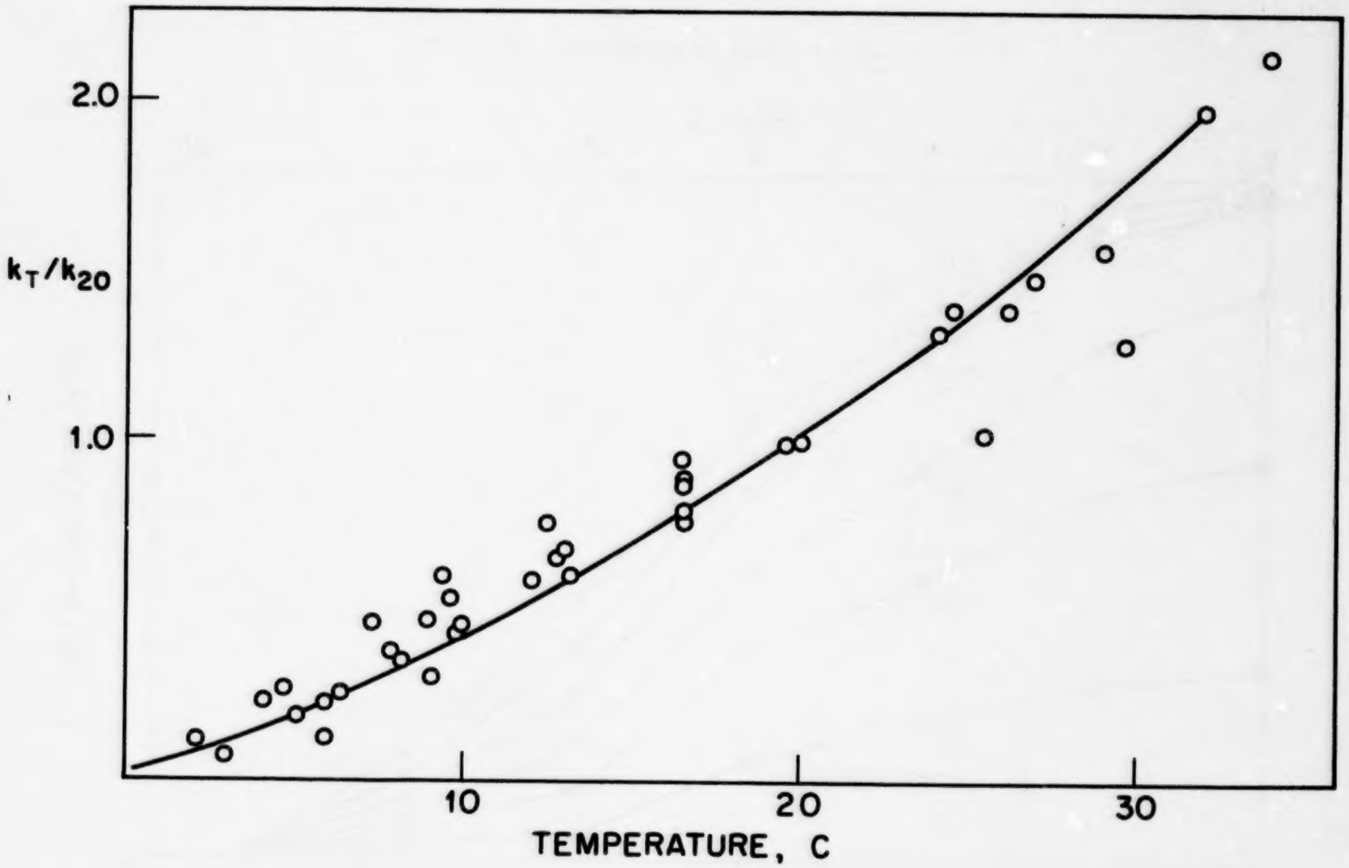

Figure 16. Temperature factor based on norm of 20 C.

values obtained were (0.53), (0.62), (0.80), and (1.0). Thus is would be predicted that removal percentages would decline by 50% with a temperature decline from 12° to 6°C.

The data at Saline for the sets enumerated behaved in a much more uniform fashion. For example, the reaction rates noted for the sets defined above were as follows: (0.773), (0.774), (0.771), and (1.0). On this basis the unit showed slight temperature adjustment from 6°C to 10°C and only a 22% reduction in reaction rates for the entire interval. Apparently the heavier attached film at Saline appears to be more insensitive to temperature changes than the thinner films of the laboratory reactors. The adaptation to produce an acclimated slime at Saline might also account for the degree of reduced sensitivity.

Figure 17 was obtained by the use of a series of bottles in a water bath. The nitrifier culture was suspended in the bottles and supplied with the standard artificial media (Appendix D). The results obtained compared to Figure 16 are quite similar. Both Figures 16 and 17 must be considered short-term responses.

Experience with the bio-film type of reactor seems to establish the fact that the degree of acclimation is an important aspect in the response of the disc system to lower temperatures. Certainly the use of short-term response values would be on the safe side.

Actual temperature corrections will depend on several factors. First, the biomass thickness is highly variable. Once a heavy slime mass is developed, it appears that because of diffusional difficulties the interior layers are starved for substrate. The onset of cold weather will slow down the use of substrate by the outer slime layers and this will then allow the interior layers to function in further removals than would otherwise be possible.

Laboratory die-away experiments would indicate that a maximum decline in biomass of 1% per day at room temperature could take place. At the cold weather temperatures of 10°C or below, die-away might be reduced to 0.5% per day or less. Thus fairly respectable removals of ammonia should be possible for much of the cold weather, if a plant operator can enter the winter period with a substantial layer of active slime on his disc system.

SPEED OF ROTATION, OXYGEN EFFECTS, AND SLIME BUILDUP

The original speed of rotation was selected after a short preliminary run in the laboratory. Results seemed to indicate that at 10 rpm (for a 2-ft (0.61 m) unit) sufficient oxygenation was produced for the laboratory

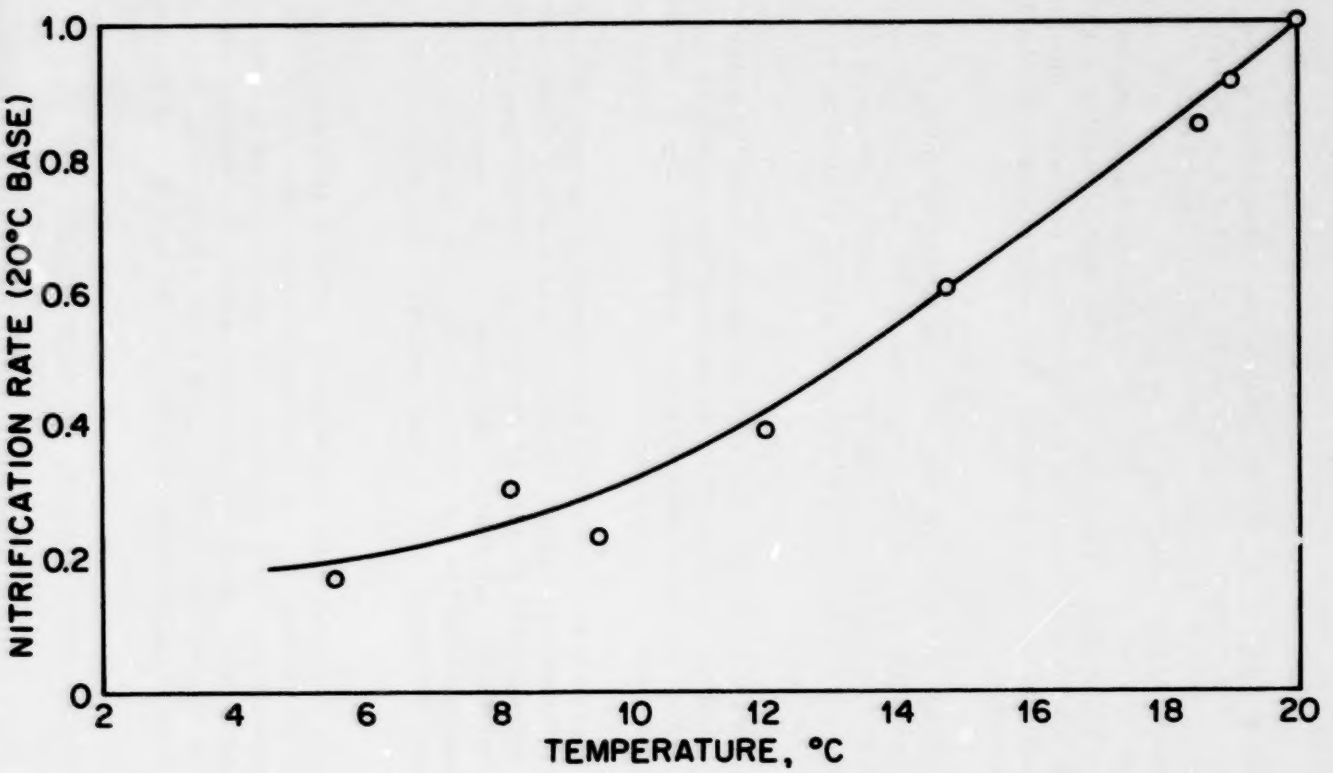

Figure 17. Temperature effects on nitrification rate.

units to complete their oxidation reactions. The peripheral velocity at 10 rpm on the 2-ft (0.61 m) laboratory model was 63 ft/min (10 m/min).

Initially therefore, all work was carried out at peripheral speeds of about 60 ft/min (10 m/min) while this value was given a further check. The first check was carried out in the laboratory since the large field unit was being kept busy with the collection of field data (Tables A-1 through A-11 and B-1 through B-10 in Appendices A and B).

Figure 18 shows the results of slowing the laboratory unit to 5 rpm then to 2.5 rpm and then speeding it back up to 7.5 rpm.

The laboratory unit at 10 rpm was removing 19 mg/ℓ of a 20-mg/ℓ ammonia-nitrogen influent. This was equivalent to a 95% removal and hence was considered a typical performance. Decreasing the speed to 5 rpm produced an immediate decline in efficiency to 92.5% removal. While 2.5% was not a large decline still the uniformity of the results was quite definite.

At 2.5 rpm the removal efficiency declined to 84% showing a rather dramatic impairment in removal efficiency. The unit was operated at this rate for a period of one week. At this point, believing that the culture might be lost, the speed was raised to 7.5 rpm and the performance returned to its former level rather immediately.

At this point, the question was raised as to whether a deficiency in oxygen was the cause of the decline in efficiency. Examination of the liquid phase of the system showed that such was not the case. Dissolved oxygen electrode measurements were made in the liquid phase regularly and always seemed to be above 4 mg/ℓ. The critical point for an oxygen deficiency however would not be in the liquid phase but in the slime layer on the disc. Unfortunately the slime layer on a moving disc was too involved a biological system for an electrode measurement of D.O. at this particular time.

Several scrapings from the disc surfaces placed in BOD bottles and provided with substrate and oxygen were studied. Typical of these results taken in the laboratory are the data shown in Figure 19. From this data the following observation seems pertinent (Table 12). While the uptake rates seemed to be very constant with time, there was a tendency for a slight break in the curve at a D.O. level of 0.5 ppm. This was interpreted to mean that the oxidation rate begins to be impaired at a D.O. concentration of 0.5 mg/ℓ for the biomass when suspended in the confines of a bottle. The same effect was obtained using a nitrifying sludge from an activated sludge process. In fact in numerous test of all types of nitrifying cultures, the same characteristic was demonstrated. Since oxidation efficiency shows impairment at oxygen levels well above this limit in the disc reactor vessels, no conclusion can be projected from this type of observation for application

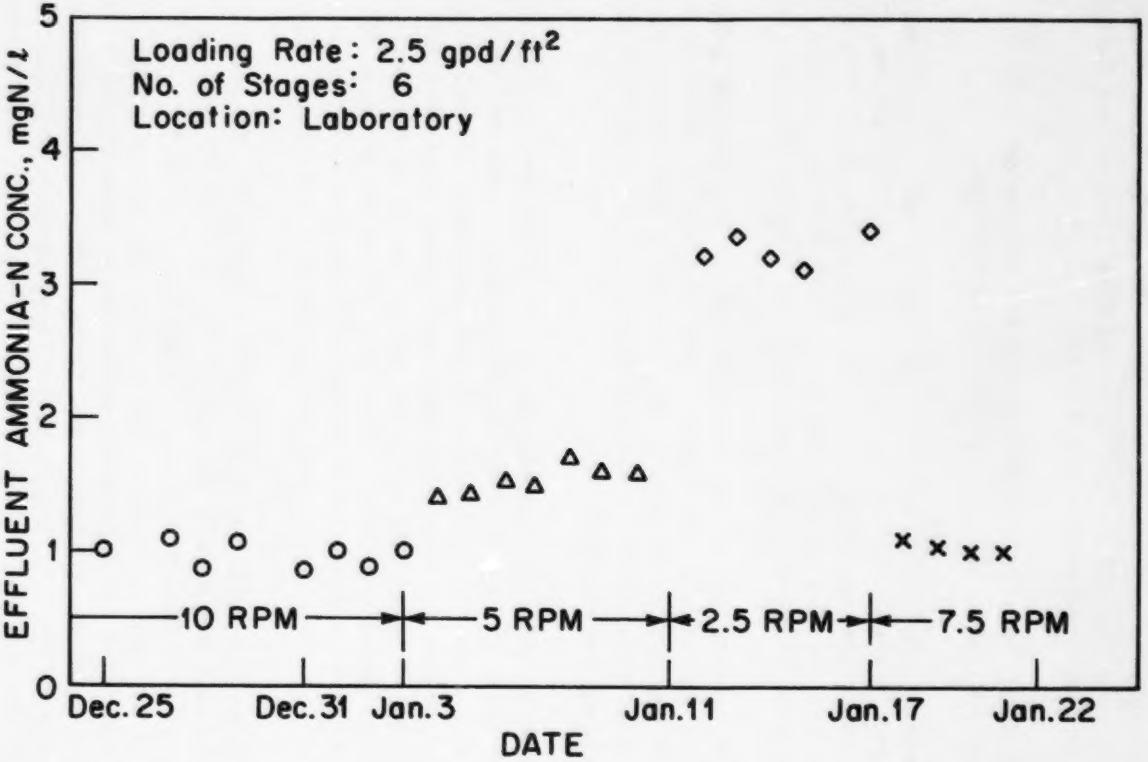

Figure 18. Effects of rotating speed on nitrification (2-ft discs).

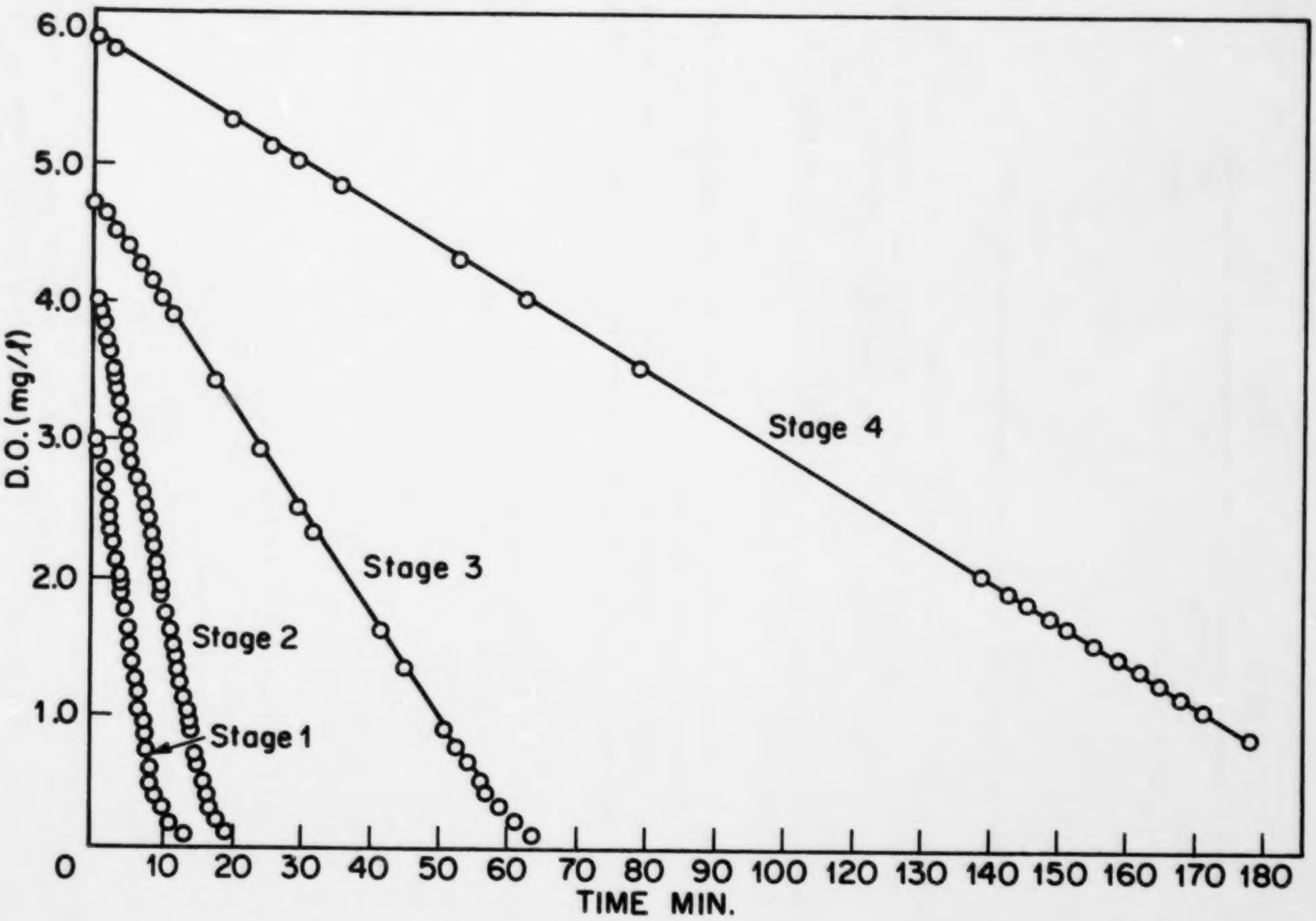

Figure 19. Oxygen uptake of disc scrapings.

to the disc system at least at this time.

TABLE 12. BIOMASS AND OXYGEN UPTAKE

Stage	D.O. uptake mg/hr	Biomass dry wt mg	D.O. uptake mg/mg biomass
1	15.0	1005	0.015
2	13.6	725	0.018
3	4.7	485	0.0097
4	1.8	270	0.0067

Additional speed tests were carried on at Saline using the 2-ft (0.61 m) diameter units. The biomass layers were heavier than the laboratory films and the oxygen diffusion problems should have been more critical. Eight stages were employed and at each speed about 24 hr was allowed for equilibrium to become established. The flow rate for this work was set at 3.0 gpd/ft^2 (122 ℓ/m^2/day).

Figure 20 gives the observed values in terms of ammonia-nitrogen removed for six different speeds and eight stages. In spite of the heavy biomass, 10 rpm seemed to give adequate oxygenation. 15 and 20 rpm showed little or no improvement while a drop to 7.5 rpm showed a loss in effienciey of about 5%.

Effluent dissolved oxygen decreased from 6.5 mg/ℓ at 20 rpm to 2.5 mg/ℓ at 2.5 rpm. At 7.5 rpm the effluent D.O. was 4.5 mg/ℓ while at 10 rpm the same parameter was 5.5 mg/ℓ. Figure 21 shows the effluent relationships better than can be described verbally. However the D.O profiles through the system (Figure 22) using an rpm of 10 as acceptable performance, would establish 3.5 mg/ℓ as the critical concentration in the bulk fluid for acceptable nitrification in the slime layer.

The 3.5 mg/ℓ concentration is the bulk concentration which was required in this case for satisfactory performance of the first three stages at the 10-rpm level. These stages contain by far the greatest weight of biomass, oxidize the largest part of the ammonia-nitrogen and therefore require the greatest amount of dissolved oxygen (see Table 13).

Visual examination indicated that the above biological films were as heavy as any that had been worked with over the two-year period of the study. Still the question of the nature of the film and its activity came up repeatedly. Visually again, it seemed that the biomass in the field unit when compared with a well seeded laboratory unit:

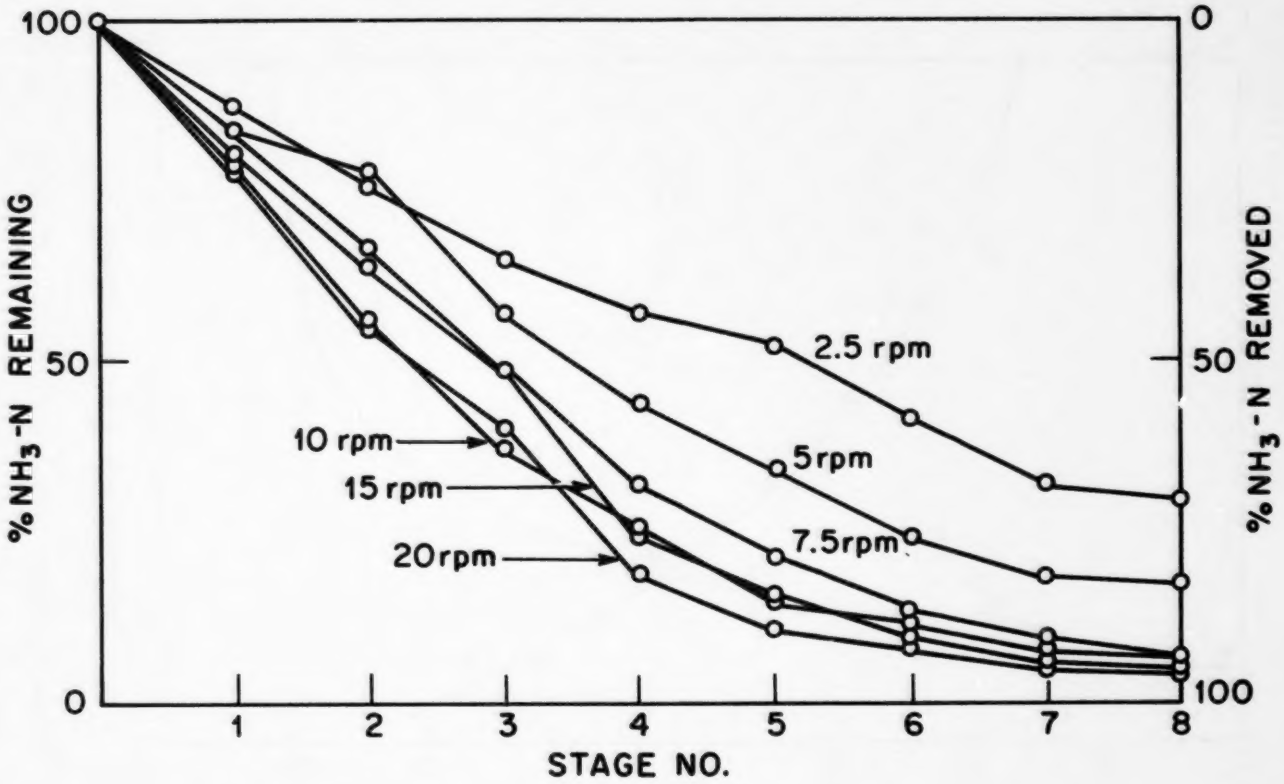

Figure 20. Rotating speed versus nitrification at Saline.

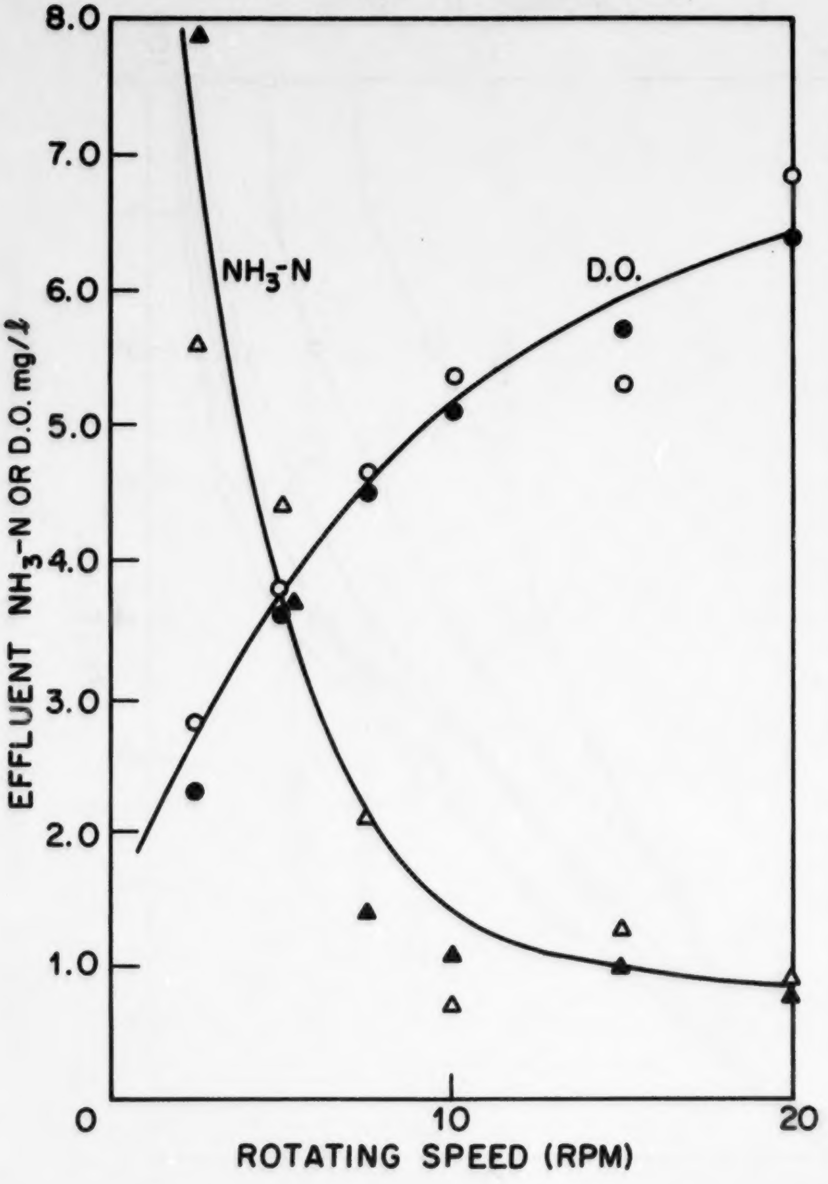

Figure 21. Rotating speed versus effluent NH_3-N and D.O. at Saline.

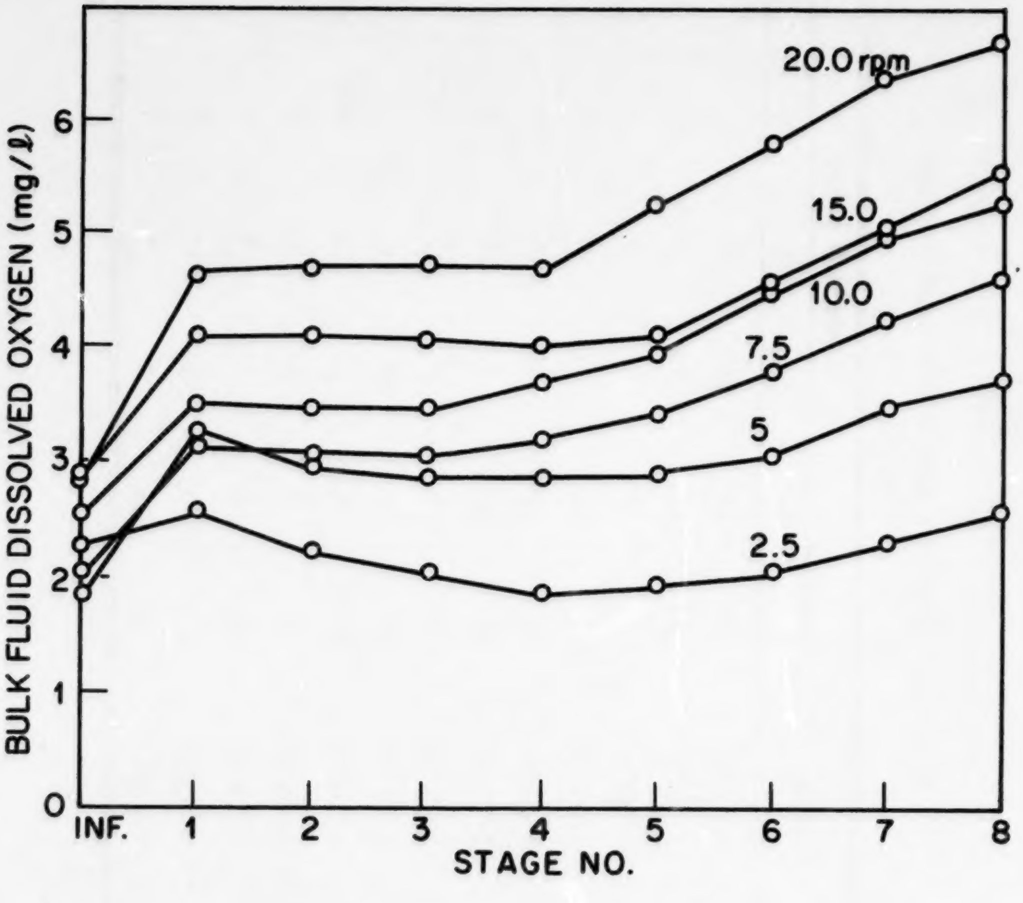

Figure 22. Rotating speed versus D.O. by stages at Saline.

TABLE 13. BOD_5 OF SALINE PILOT PLANT SAMPLES
(mg/ℓ)

Hydraulic load, ℓ/m^2/day	Date	Sampling point						
		S_1	S_2	S_3	S_4	S_5	S_6	S_7
41	12/31/75	-	17	17	19	7	4	2
	1/26/76	17	17	9	9	11	11	7
61	2/09/76	3	2	3	2	1	1	1
	3/03/76	11	8	1	0	0	1	0
81	3/10/76	18	13	10	10	9	7	4
	3/17/76	12	10	5	10	9	6	3
	3/24/76	6	4	3	3	3	2	2
	4/07/76	24	17	12	2	4	2	0
	4/14/76	10	6	3	1	1	0	1
	4/28/76	9	7	8	6	8	4	4
101	5/19/76	6	5	5	5	6	4	4
163	8/25/76	17	11	10	10	9	9	8
203	9/15/77	9	4	5	4	7	5	4

(1) became established more quickly on a new surface;
(2) reached maturity faster;
(3) was much heavier and thicker after maturation; and
(4) was less active on a unit mass basis.

It was assumed that biomass in the laboratory was much closer to a pure culture than the biomass in the field. In the Saline effluent (sample point 1) some BOD was always found tributary to the pilot unit. The amount as indicated in Table 13 was quite small and it was not thought by itself to account for the differences in the slime coats observed between the laboratory and the field units. Trace elements, suspended solids, and bacterial seed were other environmental aspects that could have affected the buildup of the biomass. In all probability all of these factors played some part in the slime layer formation.

In essence the field biomass initially grows better because of more ideal combinations of growth factors. Increased numbers of heterotrophs are likely to be part of this slime buildup. These organisms probably initially exist in a symbiotic relationship which results in better adhesion of the nitrifying seed organisms. Algal cells too are part of the complex slime layer since they inhabit the open clarifiers of the treatment works. Thus the slime growth represents an almost complete biological community in and of itself.

Catabolic activities begin to assert themselves as the slime increases in thickness. This is reflected in additional heterotrophic activity, in effect these oxidative activities result in aerobic digestion of some elements of the slime. Oxygen usage is not simply for oxidation of ammonia. The slime metabolic activity may only minimally reflect the nitrifier population.

From these considerations it seems most probable that a useful autotrophic biomass determination by a scrape and weigh technique is not possible. Nevertheless, such values measured over a span of time gave some measure of the possible range of biomass concentrations. Two field studies gave results as indicated in Figure 23. At the same time a laboratory unit loaded at an intermediate flow loading and with ammonia-nitrogen at 20 mg/ℓ was producing 95% oxidation. The discs were practically without noticeable growth. A finger held against the rotating surface revealved little or no slime. Careful scraping of large areas would yield 1 mg/in.^{2} (1.5 g/m^2) with errors of ± 30%. When field units yield weights of biomass 10 to 100 times this weight and yet give similar levels of nitrification, it seems apparent that a large part of the field biomass must be made up of heterotrophs.

Table 14 adds yet another perspective to the problem. This is, in

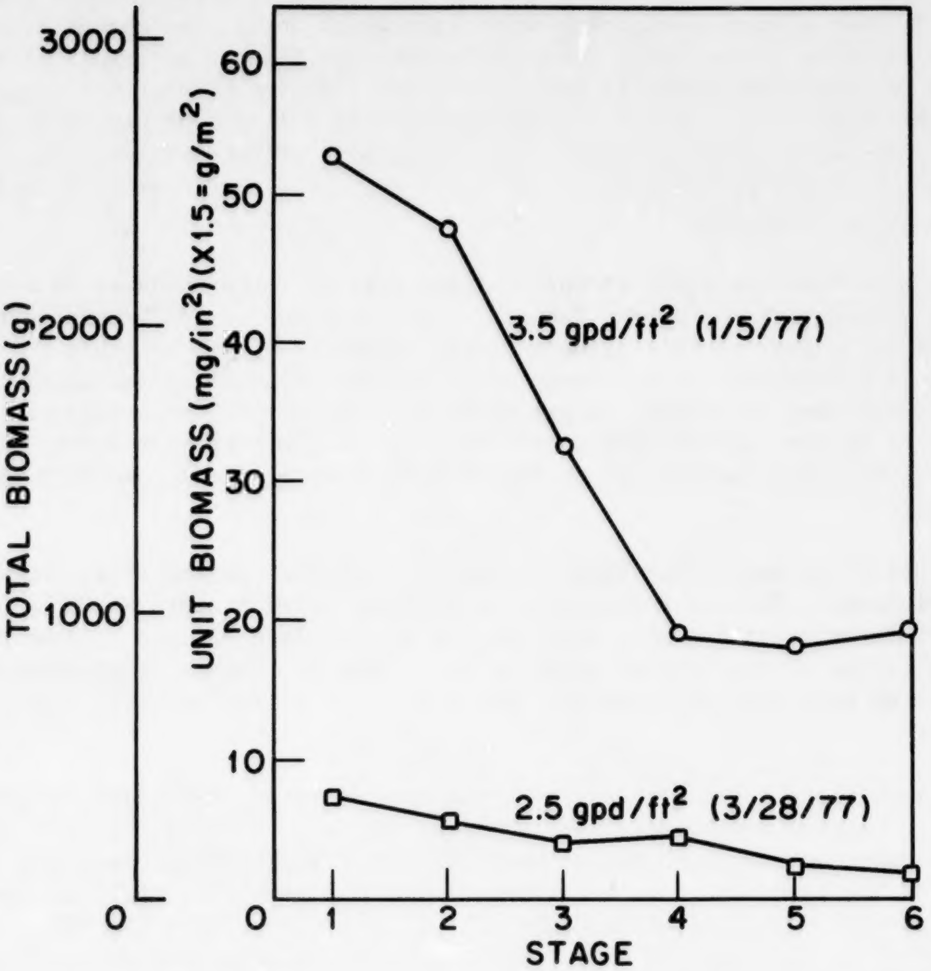

Figure 23. Typical biomass measurements.

TABLE 14. SCRAPE AND WEIGH STUDY OF SALINE BIOMASS

Stage	Area of biomass, in.^{2}	Wt. of biomass, mg	Wt. per stage, g	O_2 uptake		O_2 diff., mg/hr	Max. O_2 use per stage,* g/hr
				w/o NH_3, mg/hr	with NH_3, mg hr		
1	25	142	276	6.5	34	27.5	53.5
2	36	194	261	8.0	43	35.0	47.2
3	36	134.1	180	6.4	43	36.6	49.3
4	50	215.4	208	7.2	49	41.8	40.5
5	25	54.7	106	3.0	8.7	5.7	11.1
6	100	181.8	88	5.0	25.8	20.8	10.1
			$\sum = 1119$				$\sum = 211.7$

*These values are based on a suspended sample and hence eliminate to a large extent diffusional problems.

essence, a more complete study, typical of several that were carried out. In this case the slime was generated using an intermediate flow loading of 2.5 gpd/ft^2 (101 ℓ/m^2/day) on a six-stage unit. Since the slime was quite heavy in the initial stages and more sparse in the later stages, the area of disc selected for scraping was based on what was judged visually as being needed to give a reproducible sample. The areas chosen are shown in column 2 of Table 14. The wet slime from the respective areas was caught and carried back to the laboratory where it was processed. Representative portions were dried to a constant weight of 103°C. Other portions were suspended in bottles and the oxygen uptake rates were determined by D.O. electrodes.

Typically the solids so suspended were checked for D.O. uptake without NH_3-N present. This gave a measure of the endogenous activity. Then ammonia-nitrogen was introduced and the D.O. uptake was recorded as being the total of all activities. However, the difference of these two values was a fairly good estimate of the oxygen requirements of the total nitrifier population of the slime layer when metabolizing ammonia-nitrogen.

At that point a comparison was made between the oxygen uptake of the dispersed culture and the computed amount of oxygen required by the culture in metabolizing the ammonia-nitrogen actually oxidized by the same biomass when on the disc. For example, Table A-6 shows that on the average, of 12.2 mg/ℓ of NH_3-N, all but 0.5 mg/ℓ of NH_3-N was oxidized after passing six stages when the flow loading was 101 ℓ/m^2/day. Thus in one day the 4-ft (1.22 m) pilot unit oxidized 0.493 lb (224 g) of ammonia-nitrogen. The computations are shown below:

Actual oxygen needed to oxidize nitrogen removed would be:

Total area: 2023 ft^2

Total flow per day = 2023 x 2.5 = 5058 gal

Weight of NH_3-N:

5058 gal x 8.33 lb/gal x 11.7 gm/ℓ x 454 g/lb = 224 g N/day

Weight of necessary oxygen:

224 g N/day x 4.57 g O_2/g N = 1023 g O_2/day

Reference to Table 14 shows the dry weight of biomass per stage and the oxygen which could be used by each stage for purposes of oxidizing ammonia-nitrogen if all nitrifiers in the slime were in a suspended-type culture. In essence the summation of all six stages is 211.7 g O_2/hr (this figure has been corrected for endogenous respiration).

211.7 g O_2/hr x 24 hr/day = 5080 g O_2/day

The above computation shows that on the average, about 20% of the total number of nitrifiers in the biomass layers are participating in the actual oxidation going forward on the discs. Or, perhaps many of the nitrifiers present are working at some reduced level of their actual potential depending on their depth in the biological film and the resulting diffusional problems in their metabolism. This latter possibility seems to be the most probable mechanism.

The inference seems clear, that the nitrifiers are continually being buried by the more rapidly growing heterotrophic biomass and this creates diffusional problems, which in turn, prevents the full utilization of the entire biomass layer under steady state conditions. However, it seems amply clear also, that many of these buried organisms can be reactivated under proper conditions and thus constitute a reserve of organisms.

Table 14 indicates that the weight of biomass remains high during the first four stages and that the number of viable autotrophs also remains high through these same four stages. However reference to Table A-6 indicates that little ammonia-nitrogen is left to be oxidized by the discs at stage 4 and that the driving force is likewise low. These organisms must therefore be supported by an occasional peak or slug of ammonia-nitrogen in the form of an anomaly as previously noted. Such reserve organisms constitute a safety factor which can be valuable to the system in time of stress.

SHOCK LOADS

Close examination of the data recorded in Tables A-1 through A-11, Appendix A, indicates that when conditioned for a given substrate loading and removal, the disc tends to extract substrate at that level. If a higher loading becomes tributary to the system, the unit will extract some small portion of the increase but pass the remainder to the effluent. Reference to the latter portion of Table A-3 (Appendix A) illustrates this point. The appropriate place in Table A-3 is indicated by the critical dates of sampling (12/29 through 2/6).

Note that for an initial period of over two weeks in this designated time interval, the disc system operated with a substrate concentration between 13.4 and 16.0 mg/ℓ. The effluent was constantly at 0.1 mg/ℓ. On 1/21 the influent jumped from 15 to 16.4 mg/ℓ. The effluent responded by increasing from 0.1 to 0.5 mg/ℓ; on 1/23 the influent increased to 18 mg/ℓ and the effluent to 1.0 mg/ℓ; on 1/26 the influent increased to 22.2 mg/ℓ and the effluent to 1.4 mg/ℓ. This interval of higher loadings constituted about a week which was sufficient for acclimation to a somewhat higher substrate concentration and thus further loadings at increased levels resulted in higher removals as typified by the results on 2/4 and 2/6.

It should be noted that the samples recorded in Table A-3 were 24-hr composits and hence constituted long-term (24-hr) impacts on the system. There are many such examples of this type of response throughout Tables A-1 through A-11 (Appendix A). The reader can extract other examples if he chooses. Two points however should probably be emphasized here. First it seems equally likely that in operation, the substrate strength will drop about as often as it will rise. Obviously, the disc system will respond well to a drop in concentration.

Secondly, for most changing patterns involving modest long-term increases, about one week of acclimation will provide the necessary increase in biomass to adequately handle the increase in substrate.

Table A-3 reflects a flow loading which is essentially doubled to produce Table A-5. Appropriate acclimation time was allowed and the results in Table A-5 show that the disc system responds well to a doubling of flow in this range and with acclimation.

The question which arises is, since the 24-hr shock constitutes a long-term shock, would some shorter time become a short-term (more easily absorbed) shock.

The first shock study was set up in the laboratory. The study consisted of 1-, 2-, and 4-hr hydraulic flow shocks during which time the flow was doubled for the designated period of time. This change simply raised the flow from 1.25 gal/ft^2/day (51 ℓ/m^2/day) to 2.5 gal/ft^2/day (102 ℓ/m^2/day). It should be noted that the higher flow is the value used in Table A-6 of Appendix A and represents a flow loading which the disc can easily be acclimated to accept with about one week of adverse results. After this period of acclimation the system will provide about 95% removal of ammonia-nitrogen. In this case however no time would be available for acclimation and this series of tests should give a measure of short-term response to such a shock.

Figure 24 shows the continuous response in the six-stage laboratory disc effluent when the 1-, 2-, and 4-hr hydraulic shocks are applied. Figures A-9, A-10, and A-11 (Appendix A) give the intermediate, stage by stage, values. Table 15 shows the total removal of the shock load added and the maximum discharge concentrations of ammonia-nitrogen under each of the shock load conditions.

Reference to Table 15 shows that during the 1-hr shock an additional 0.6 g of ammonia-nitrogen was added to the disc system and that 87% of that shock was oxidized. This would constitute little or no impairment of effluent as revealed by a 24-hr composite. The 2-hr flow shock and the 4-hr flow shock are both rather serious in their effect on the efficiency. These time

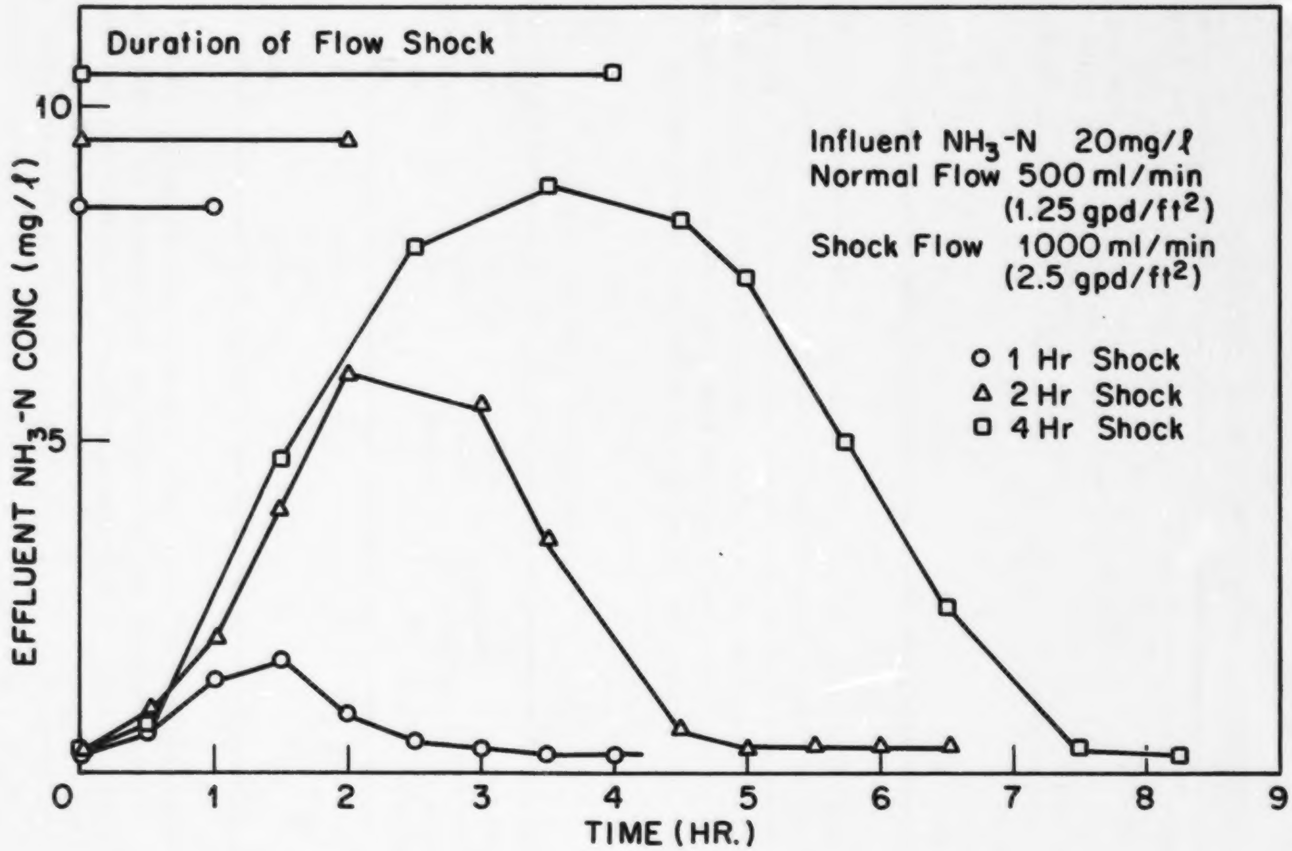

Figure 24. Flow shock effects.

periods are therefore serious enough to be considered long term and hence to require some acclimation.

TABLE 15. FLOW SHOCK EVALUATION

Hydraulic application rate, ℓ/m^2/day	Shock duration, hr	Total NH_3-N added, g	Percent of NH_3-N shock removed	Maximum NH_3-N discharge conc. mg/ℓ
102	1	0.6	87.2	1.7
102	2	1.2	43.9	6.0
102	4	2.4	27.1	8.1

A concentration shock was handled in the same fashion as the flow shock. Figure 25 shows the overall response while the nests of curves for intermediate values are located in Appendix A (Figures A-12, A-13, and A-14). Table 16 indicates that concentration shocks are not as serious as flow shocks. Since all other factors have been constant except driving force, this latter factor must be important in shock load accommodation.

TABLE 16. CONCENTRATION SHOCK EVALUATION

Hydraulic application rate, ℓ/m^2/day	Shock duration, hr	Total NH_3-N added, g	Percent of NH_3-N shock removed	Maximum NH_3-N discharge conc. mg/ℓ
51	1	0.6	70.7	1.2
51	2	1.2	67.1	5.0
51	4	2.4	82.1	5.0

Further analysis of these data is carried out in Tables 17 and 18. The results indicate that the distribution of biomass, as revealed by the nitrogen removal data, is not always regular. This fact has been pointed out previously. Assuming that biomass and nitrogen oxidation are proportional, four of the six tests made in this case have biomass which is a maximum on stage 1 and tapers down to a low value on stage 6. These would be the 1- and 2-hr flow shock tests and the 1- and 4-hr concentration shock tests. The two reamining series have peak biomass on stage 3. It should be

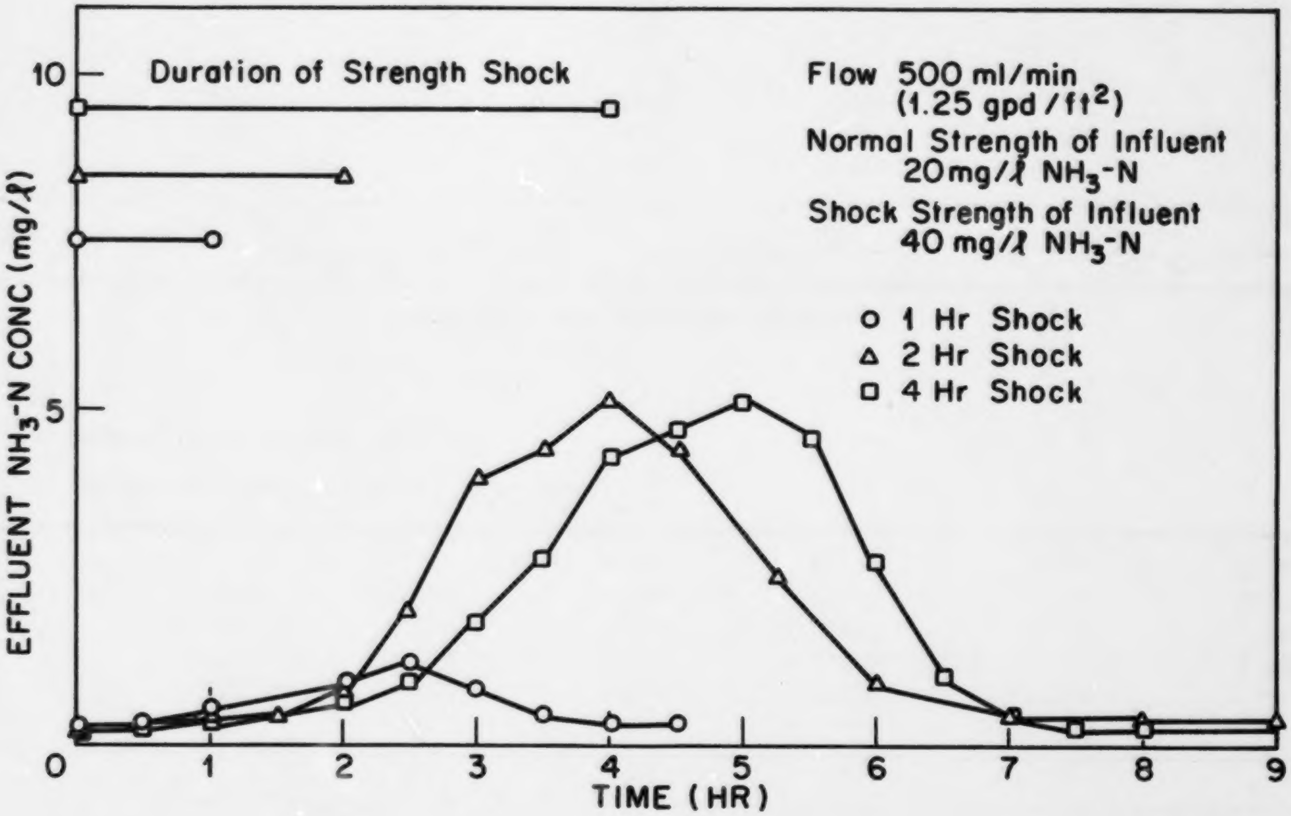

Figure 25. Strength shock effects.

TABLE 17. FLOW SHOCK DATA

Stage	1-hr shock		2-hr shock		4-hr shock	
	R_{ss}*	R_{sl}†	R_{ss}	R_{sl}	R_{ss}	R_{sl}
1	0.945	--	1.134	--	0.918	--
2	0.810	0.053	0.846	0.155	1.505	--
3	0.783	0.363	1.134	0.384	2.066	0.063
4	0.095	0.097	0.144	0.156	0.357	0.342
5	0.027	0.048	0.072	0.075	0.128	0.161
6	0	0.037	0.018	0.048	0.051	0.168

*R_{ss} = removal at steady state prior to shock.

†R_{sl} = removal of shock load (g).

TABLE 18. CONCENTRATION SHOCK DATA

Stage	1-hr shock		2-hr shock		4-hr shock	
	R_{ss}	R_{sl}	R_{ss}	R_{sl}	R_{ss}	R_{sl}
1	0.945	--	1.283	0.095	1.733	--
2	0.878	0.148	1.682	--	1.238	0.109
3	0.797	0.217	1.995	0.390	1.058	1.209
4	0.122	0.025	0.228	0.244	0.113	0.212
5	0.040	0.032	0.114	0.157	0.045	0.104
6	0.013	0.025	0.029	0.047	0.045	0.104

noted then, that all these tests were made on a series of six stages which were fed at a constant flow of 1.25 gpd/ft^2 (51 ℓ/m^2/day) and at 20 mg/ℓ of ammonia-nitrogen during their steady state development. In other words they should have had similar biomass developments but obviously were widely different.

Based on the steady state oxidation levels achieved before the shock loads were initiated, Tables 17 and 18 give the entire series of R_{ss} values. (R_{ss} is defined as the steady state removal of ammonia-nitrogen achieved by that stage prior to the appropriate shock load. R_{sl} is defined as the removal of ammonia-nitrogen by the appropriate stage during the shock load.) Examination of the R_{ss} terms for all stage 1 shock studies reveals that even when they are not the highest in the series, they are usually quite substantial. It would therefore be expected that whatever removal of the shock load does take plase, at least a part of it would be accomplished by the biomass on stage 1. In five of the six shock load studies no increment of the shock load is affected to any extent on stage 1. In all cases but one the peak is taken at stage 3 whether or not that point is the peak of biomass in the systen. As a result of these consideration, while biomass must be considered important in the accommodation of a shock load, it is obviously not the major factor involved. The research to this point would tend to emphasize previous history of development, activity of the biomass, and diffusional problems as important factors as well as driving force and detention time.

Whatever the important factors involved in the accommodation of a shock load, it seems apparent that stages 1 and 2 are totally ineffective in this activity for any shock load of consequence. This emphasizes again the value of more stages rather than fewer stages where such an alternative is possible.

Table 15 indicates that 87.2% of the shock load tributary to the disc system during a 1-hr flow shock is removed. The regularity of the trend in removal percentages suggests that less than 1-hr shocks can easily be accommodated while shock flows of less than 100% additional flow can probably be adsorbed for proportionally longer periods of time.

It should be emphasized that concentration shocks appear to be accommodated in a better fashion than flow shocks for the same weight of ammonia-nitrogen substrate. This fact implies that time is important as well as driving force when acclimation is not provided (as when a short-time shock load occurs).

If a rational approach is taken in the analysis of the response to a shock load the following question might be asked as a first step:

> "Is the autotrophic biomass basically a major factor in the removal experienced?"

The 4-hr shock concentration test removed the largest mass of the shock fed. As a result it would probably be the best condition to analyze. Table 16 shows 2.28 g applied and 1.90 g removed. Further, the distribution of biomass would show the following percentages:

TABLE 19. DISTRIBUTION OF BIOMASS AND SHOCK REMOVAL

Stage	Percentage of total biomass	Percentage of shock removed	Ratio of column 3/ column 2
1	40.8	0.0	0.0
2	29.3	5.7	0.2
3	25.0	63.6	2.5
4	2.7	11.1	4.1
5	1.1	14.1	12.8
6	1.1	5.5	5.0
	Σ = 100.0	Σ = 100.0	

This computation shows that while stage 1 has 40% of the total biomass, it removed none of the shock load. Stage 2 with 29% of the total biomass removes only 6% of the shock load. But stage 3 with 25% of the biomass removes 63% of the shock load. Stages 4, 5, and 6 remove lesser percentages. However if the amount removed is compared to the biomass on that stage some outstanding performances are noted. For example only 1% of the total biomass existed on stage 5 and yet it removed 14% of the shock load applied. If stage 1 had performed in similar fashion, most of the shock load in question would have been removed at that point. It must be concluded that, in answer to the question posed, biomass and specifically autotrophic biomass does not alone account for shock load removals.

Reference to Figure A-14 (Appendix A) shows the profile of the ammonia-nitrogen species by stage for the 4-hr concentration shock loading. Stage 1 had an average steady state influent ammonia-nitrogen of 12 mg/ℓ and an effluent of 7.5 mg/ℓ. With a low growth rate and an excess ammonia of 7.5 mg/ℓ, a sudden increase in that nutrient element for a short period of time could probably not affect the stage 1 biomass. Stage 2 had an influent of 7.5 mg/ℓ and an effluent of 4 mg/ℓ. Again the effect of additional ammonia would be minimal. However by the time stage 3 is reached, the biomass under steady state, has been somewhat starved. There is still substantial biomass on stage 3 and hence resistance to diffusion, but the steady state concentration in the reactor was only about 1 mg/ℓ. This was probably too low a concentration to nourish the film at an acceptable rate. Hence, when a slug of nutrient such as was applied during the 4-hr shock load became available, it was quickly metabolized. Unfortunately as the degree of starvation increases throughout the remaining stages, the autotrophic biomass is decreasing. As a result the capacity of the system to counteract a shock load beyond stage 3 is not substantial.

A word or two here about driving force seems in order. It is possible in a concentration shock load situation to have only a fraction of the biomass fully active as illustrated in Table 14. Thus the biomass is available, the substrate becomes available (from the shock load) as well as the driving force for that substrate. Then the problem may be, that the oxygen concentration in the bulk fluid is not sufficiently high to provide an adequate driving force for that component. In other words, the term driving force covers more than a single ingredient.

At this point it might be appropriate to review the points of interest bearing on the questions of mechanism, biomass, sloughing, and shock load potential. All of these functions appear to be interrelated. The study to date seems to indicate that the following theory may be proposed:

(1) The autotrophs which carry on nitrification appear to be capable of remaining viable under conditions where little or no substrate is available to them for protracted period of time. The die-off rate in effect is very low. In one case where a culture of 370 mg/ℓ was aerated without substrate over a period of two weeks, the loss of biomass amounted to 0.01 g/g/day.

(2) Such starved organisms age or decline slowly in their ability to metabolize their normal substrate. This probably is best described as a form of reduced activity. A culture of organisms of low activity can be restored to high activity with about three days of intensive feeding in an environment of excess oxygen and other required nutrients.

(3) As a result of the above, with each level of biomass must be associated an activity factor which reflects the ability of that biomass to metabolize its substrate expressed as mg of NH_3-N/mg of biomass/hr.

(4) In the bio-disc system, each stage in a series of stages has a typical biomass. Each stage in turn has to be cultured at a lower and lower level of substrate reflecting the removal of those stages lying above it in the series. Thus each stage in a series operation might be expected to have a lower activity factor than the previous stage.

Figure 19 and Table 12, show the relative oxygen uptake rates by stage for the first four stages in a series. These values reflect approximately, the rate of ammonia-nitrogen oxidation or activity of the autotrophs because the responses shown were corrected for endogenous respiration. It should be noted that results in Table 12 were obtained under conditions where the entire thickness of biomass was scraped from the discs, dispersed in a bottle of oxygenated substrate, and the oxygen decline monitored by electrode. The straight-line portions of Figure 19 thus reflect a condition where both food and oxygen were in excess and where diffusion into the film has virtually been eliminated.

(5) If the biological growth in (4) above had been anchored in place on a series of discs, the decline in activity would still be present but would in addition reflect the effects of diffusion into the film, decline of substrate with staging, and most critical of all, oxygen limitation in the early stages. If one examines the results for stages 1 and 2, in the data reflecting the rpm studies, specifically Figure 20, it is apparent that, all else being constant, as the rotational speed goes up for a given stage, the ammonia-nitrogen removal efficiency does improve. This reinforces the belief that oxygen limitation exists.

It appears that the same can be said for all stages except for the fact that the substrate concentration is declining at the same time. It actually reaches such low levels in the latter stages that the reaction is substrate limited as suggested by Figure 28. Because of the lower demand for oxygen this element actually increases in the bulk fluid of the latter stages as indicated by Figure 22.

(6) It appears that at a fixed rpm level, little lattitude exists in the oxygen resources. Hence, the substrate to be oxidized on a given stage can only be increased up to a fixed level suggested by Figure 9 as (3 $g/m^2/day$). At that substrate level, that stage becomes oxygen limited. No matter what level of ammonia-nitrogen either as substrate or driving force is applied to whatever level of biomass exists at that point, none of the additional substrate can be utilized. This then would be true as long as the oxygen limitation persists. Of course such a situation causes the excess ammonia-nitrogen to pass on down the series of discs providing food for the next stage (when such exists).

(7) An oxygen limitation in the autotrophic community does not stop growth of heterotrophs since they compete more favorably for oxygen than do the nitrifiers.

(8) As the heterotrophs continue to grow beyond the limit of growth for the autotrophs, a continual burial of the autotrophs takes place. This is due to the slime mass generated by the heterotrophs and would apply to all stages. However, it is most noticeable in the first few stages, say 1 through 4, which get most of the available BOD tributary to the system.

(9) As the autotrophs become buried, diffusion makes it difficult for them to keep metabolizing the same level of substrate defined by Figure 9 (0.3 $g/m^2/day$). Therefore, a reduction in their activity takes place producing a concurrent rise in ammonia-nitrogen in the bulk fluid (previously defined as an anomaly). This rise in substrate level proceeds to the next stage generating a pulse of food and sustenance for the previously unfed autotrophs on further stages down the series.

(10) In the meanwhile new autotrophs beging to form a new layer of more active nitrifiers above the original and now buried layer of autotrophs. These can now grow since reduced activity has relieved the previous oxygen limitations to some extent. As a result of the above, layer upon layer of biomass is built up. The deeper layers are older and less active but each metabolizes its aliquot of available substrate. Each is limited only by the amount of biomass in the layer, its unique activity factor and the diffusional problems each has with oxygen and substrate.

(11) It seems clear that there are many layers of organisms living on reduced levels of substrate. This fact must be stressed since all bio-films which have been examined have large numbers of nitrifiers which are not being fully utilized. Table 14 and the associated computation show an average of 20% of the available autotrophs were being used in that case. The percentage however, is highly variable and reflects the pulses or surges of flow and substrate strength tributary to the series of discs. Table 20 shows a further breakdown of the data covered in Table 14.

Table 14 showed an average of 20% of the available nitrifiers overall, were actively being used over the six stages. Table 20 (line 5) indicates however, that on stage 1, 35% of the available nitrifiers are used. This figure drops to 24% on the second stage, 16% on stage 3, and 4% on stage 4. Thus, 84% of the nitrifiers on stage 3 and 96% on stage 4 are not being fed regularly (they are in effect starved). In addition, oxygen is increasingly available to those stages. All that is needed is the proper substrate for these organisms to assert themselves. This is what takes place during a shock load. The data in Table 19, columns

3 and 4, show that any shock load is taken by the latter stages. These lie in a region defined by relatively high biomass, acceptable oxygen concentrations and at least intermittent starvation.

TABLE 20. FURTHER ANALYSIS OF TABLE 14

System component	Stage					
	1	2	3	4	5	6
NH_3-N conc. driving force (mg/ℓ)	7.0	3.9	1.7	1.3	0.7	0.5
NH_3-N oxidized (mg/ℓ)	5.2	3.1	2.2	0.4	0.6	0.5
O_2 required by NH_3-N (g/day)	454	271	192	35	52	17
O_2 used by same slime when dispersed (g/day)	1284	1133	1183	972	266	242
Ratio line 3 / line 4	0.35	0.24	0.16	0.04	0.20	0.07
Total biomass (g)	276	261	180	208	106	88

(12) It seems clear that the disc system has extra organisms in the depth of the bio-film on each stage as well as on successive stages down the series. These two separate resources appear to be safety factors and yet to serve different purposes. For example, a typical response might show (Table 19) 0.0% of shock load taken by stages 1 and 2 while stages 3 and 4 take a very large percentage of that same shock. The starved lower layers of stages 1 and 2 happened to be oxygen limited and unable to perform since these stages were fully loaded. Hence, the shock load had to move down the series to regions with unlimited oxygen. The value of unfed or starved biomass farther down the series of stages thus seems well defined. But, what is the value of the unfed or starved biomass in the depths of stages 1 and 2? In essence these lower layers of starved nitrifiers provide the source of the seed orgaisms and the origin of the new layers that are continually being formed as observed in point (10) above.

This resource is quite beneficial. Once during the two years of study covered by this project, a toxic contaminant destroyed large masses of biological film. The biomass on stages 1 and 2 of the pilot unit dropped by 50%. The performance of these stages declined markedly. The steady state load was taken up by stages 3, 4, and 5 and the reseeding of stages 1 and 2 was accomplished by the starved lower levels of organisms on those stages. What was remarkable was that merely a ripple was noticed in the overall performance. Further, stages 1 and 2 returned to full activity within three days.

The above 12 points describe how the response of the disc system is generated and how the biological forces combine with the mechanical forces to become self-regulating mechanisms to distribute the substrate load.

From all the available facts, it seemed logical that under conditions where each stage was fully loaded at about 3 g/m^2/day of ammonia-nitrogen, the unit should develop its maximum biomass on all stages. Theory would say that even with high levels of autotrophs on all stages and 3.5 mg/ℓ of dissolved oxygen everywhere, no shock load would be picked up on any stage because no starvation would exist on any stage.

To check this assertion an eight-stage unit was set up at Saline with a flow of 3 gpd/ft^2 (122 ℓ/m^2/day). Such a unit should be throught of as being flow loaded at 24 gpd/ft^2 (978 ℓ/m^2/day) on the first stage and hence 4 gpd/ft^2 (163 ℓ/m^2/day) on six stages. It should be noted on Figure 8 that such a unit is fully loaded. This is revealed by the virtual lack of curvature in a typical flow loading curve.

Figure 26 shows the results obtained on a per stage basis when the unit was given a 4-hr concentration shock. The integrated areas under the curves reveal that in this case, none of the shock load was touched by the pilot unit. The curves are impressive since the influent concentration at Saline was relatively stable over the period required for the test (7 hr). This was normally not the case which would have tended to distort this type of data if it had happened. At any rate, the theory proposed above seems fully validated by such test results.

FLOW REVERSAL

In activated sludge work or other biological research, the effect of shock loads is often very detrimental to the activity of the culture. Nitrifying cultures are far less prone to show the impact of such shock conditions. In fact the feeling may be generated after working with such autotrophs that they act more like organic catalysts than biological cultures.

To cite a few example of this type of response which have been previously indicated in these data but which were perhaps overlooked by the

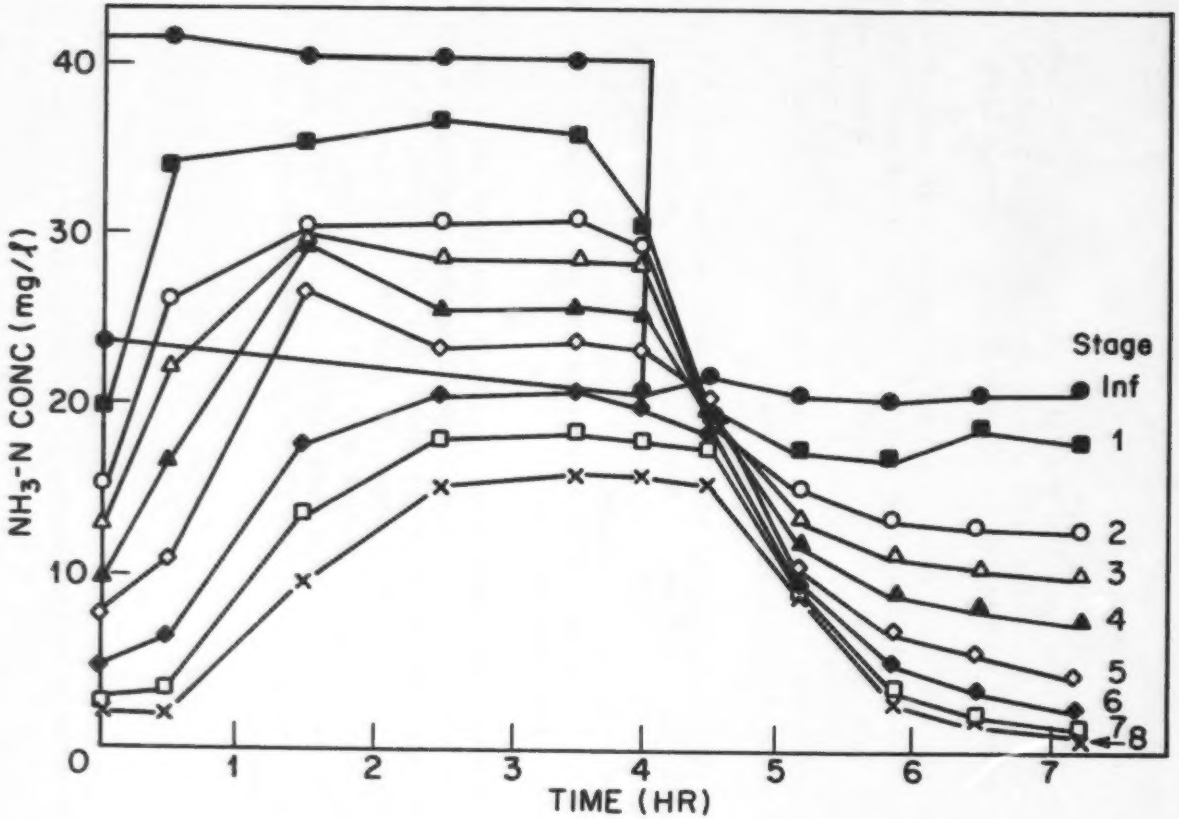

Figure 26. Profiles of 4-hr shock load at Saline.

casual reader. Note the following:

(1) Reference to Figures A-6 through A-11 covering shock loads indicates that when the flow or strength was returned to its original steady state condition after a shock, the ammonia removal returned to its original level in all six cases. Reflection on this fact indicates that even when the flow or strength was raised for up to 7 hr, apparently the culture remained unchanged and thus could give the exact response 7 hr later, which was exhibited originally.

(2) With lowering of rotating speed and the resulting oxygen depression, even though this effect took place over a 7-day period, the discs resumed their normal level of metabolism very quickly when speed was resumed (the worst case took about 24 hr to recover).

(3) The response to temperature was very similar. In essence the recovery from a very adverse temperature was almost instantaneous, when a change to a more normal temperature was applied.

In essence it has been established that while nitrification biomass grows very slowly, it dies away much more slowly. On this basis, if biomass can be induced to grow by intermittent feeding, it might be possible to grow a great deal of additional biomass on the last few stages of a series. It is in this portion of a disc system that a deficiency of biomass may exist in a moderately loaded system.

Head loss through an RBS system is also usually low and there is no reason why the direction of flow should not be altered at will. If the direction of flow is reversed each day, wouldn't the last two stages or those which have low biomass begin to experience biomass build-up to the same level as the original first two stages? This should produce a more uniform distribution of biomass across the various stages of the unit.

In which case, for any given direction of flow, the last few stages will have a high but partially starved level of biomass. This meets one of the pre-conditions which was theorized as being necessary for coping with a shock load.

Overall distribution of substrate and oxygen limitations would also have to be considered. These latter conditions have to be controlled by devices which are yet to be developed. In this case oxygen might be adjusted by speed control of the discs or recirculating pumps involving aeration devices, etc. Substrate might be controlled by D.O. electrodes combined with ammonia-nitrogen electrodes.

This last portion of the considerations would have to be considered research beyond the scope of this effort. However, the portion on flow reversal seemed well worth attempting. This phase of the work was tried first in the laboratory. The six stages were activated normally then the flow was reversed. The removal by stage had been a curvilinear relationship for the most part paralleling the biomass distribution. After one month of continually reversing flow every 24 hr the biomass and the ammonia removal trend had not changed. In essence when the flow was reversed, the removals remained fixed in the same pattern as defined before reversal took place. It seemed possible that the problem of seeding was at fault. A unit was therefore set up at Saline for the study of flow reversal. After 7 days of reversal the ammonia removal profile was the same in each direction. Color, biomass density and all other criteria indicated that the biomass was uniformly distributed throughout the unit.

Table 21 shows the development of this biomass which was equally effective in both directions and which required a little over one week for its total development.

Obviously, in this mode, the last few stages in either direction have a lot more biomass and are certainly starved for substrate. It would appear that additional work will be necessary to validate the overall beneficial characteristics of flow reversal.

SIMPLIFIED KINETICS APPLIED TO RBS NITRIFICATION

Development of a complete mathematical model describing the bio-disc even if restricted to the aspect of nitrification appears to be a remote possibility at this juncture. The ingredients involved in the nurture of the biological culture are difficult to handle quantitatively.

First the biomass is extremely variable. The admixtures with heterotrophs appears to be almost infinite. As the heterotrophs increase in numbers, the resistance to diffusion likewise increases. The autotrophs respond by growing at lower and lower rates. Thus a well developed bio-film represents an almost infinite spectrum of biological growth rates and diffusivity problems.

The following technique is presented because it appears to be confirmed by the assembled data. Several models involving inhibition, etc., have been tried and found to be inapplicable. The following basic assumptions in this simplified technique apply:

(a) Complete mixing occurs in each stage. (Tracer Study, see Figure D-4.)

TABLE 21. RESPONSE OF PILOT UNIT TO INITIATION OF FLOW REVERSAL

Date, 1977	Direction of flow	Influent	Stage								Influent
			1	2	3	4	5	6	7	8	
5/14	→	27.0*	27.2	27.4	27.7	27.1	27.1	26.9	26.8	26.3	
5/18	←		11.3	12.3	13.4	14.3	15.2	16.1	16.8	17.8	18.7
5/20	→	32.5	30.5	27.0	24.0	22.4	19.5	17.3	15.0	12.7	
5/22	←		1.0	1.1	1.2	1.7	2.7	5.7	9.1	12.7	18.3
5/24	→	21.0	15.2	11.8	6.2	3.1	2.0	1.3	1.0	0.8	

*All figures represent NH_3-N in mg/ℓ.

(b) All necessary nutrients are present in excess (with a staged approach to treatment and D.O. above 3.5 mg/ℓ, this is basically true).

(c) Monod equation for growth rate is applicable:

$$\mu = \mu_{max} \frac{C}{K_S + C}$$

where μ = specific growth rate, 1/hr

μ_{max} = maximum specific growth rate, 1/hr

K_S = half saturation coefficient, mg/ℓ

C = substrate concentration, mg/ℓ

X = biomass concentration, mg/m^2

(d) There is no significant loss of substrate within the system (no sink)

(e) The presence of organic carbon and heterotrophic growth does not interfere with nitrification.

The substrate balance then can be expressed as:

$$V \cdot \frac{dC}{dt} = QC_o - QC - A \frac{\mu_{max}}{Y} X \frac{C}{K_S + C}$$

where V = volume of a stage, ℓ

Q = flow rate, ℓ/hr

C = limiting substrate concentration, mg/ℓ

A = surface area per stage, m^2/stage

Y = yield coefficient, mg cells/mg substrate

The above equation can be rearranged to yield:

$$\frac{dC}{dt} = \frac{Q}{V}(C_o - C) - \left(\frac{A}{V} \cdot \frac{\mu_{max}}{Y}\right) X \frac{C}{K_S + C}$$

$$\frac{dC}{dt} = \frac{Q}{V}(C_o - C) - K_1 \frac{C}{K_s + C}$$

Assuming $$K_1 = \frac{A}{V} \cdot \frac{\mu_{max}}{Y} X$$

This assumption is based on an inability to determine appropriate values for μ_{max}, Y, and X. The analogy is applied as follows to ammonia, nitrite and nitrate nitrogen (organic nitrogen is omitted as unimportant).

MATERIAL BALANCE RELATIONSHIPS

First Stage

$$\frac{dA_1}{dt} = \frac{Q}{V}(A_o - A_1) - K_1 \cdot A_1/(K_{ss} + A_1)$$

$$\frac{dB_1}{dt} = \frac{Q}{V}(B_o - B_1) + K_1 \cdot A_1/(K_{ss} + A_1) - K_2B_1/(K_{sb} + B_1)$$

$$\frac{dC_1}{dt} = \frac{Q}{V}(C_o - C_1) + K_2 \cdot B_1/(K_{sb} + B_1)$$

Second Stage

$$\frac{dA}{dt} = \frac{Q}{V}(A_1 - A_2) - K_1 \cdot A_2/(K_{ss} + A_2)$$

$$\frac{dB_2}{dt} = \frac{Q}{V}(B_1 - B_2) + K_1 \cdot A_2/(K_{ss} + A_2) - K_2 \cdot B_2/(K_{sb} + B_2)$$

$$\frac{dC_2}{dt} = \frac{Q}{V} = (C_1 - C_2) + K_2 \cdot B_2/(K_{sb} + B_2)$$

Third Stage

$$\frac{dA_3}{dt} = \frac{Q}{V}(A_2 - A_3) - K_1 \cdot A_3/(K_{ss} + A_3)$$

$$\frac{dB_3}{dt} = \frac{Q}{V}(B_2 - B_3) + K_1 \cdot A_3/(K_{ss} + A_3) - K_2 \cdot B_3/(K_{sb} + B_3)$$

$$\frac{dC_3}{dt} = \frac{Q}{V}(C_2 - C_3) + K_2 \cdot B_3/(K_{sb} + B_3)$$

Fourth Stage

$$\frac{dA_4}{dt} = \frac{Q}{V}(A_3 - A_4) - K_1 \cdot A_4/(K_{ss} + A_4)$$

$$\frac{dB_4}{dt} = \frac{Q}{V}(B_3 - B_4) + K_1 \cdot A_4/(K_{ss} + A_4) - K_2 \cdot B_4/(K_{sb} + B_4)$$

$$\frac{dC_4}{dt} = \frac{Q}{V}(C_3 - C_4) + K_2 \cdot B_4/(K_{sb} + B_4)$$

Fifth Stage

$$\frac{dA_5}{dt} = \frac{Q}{V}(A_4 - A_5) - K_1 \cdot A_5/(K_{ss} + A_5)$$

$$\frac{dB_5}{dt} = \frac{Q}{V}(B_4 - B_5) + K_1 \cdot A_5/(K_{ss} + A_5) - K_2 \cdot B_5/(K_{sb} + B_5)$$

$$\frac{dC_5}{dt} = \frac{Q}{V}(C_4 - C_5) + K_2 \cdot B_5/(K_{sb} + B_5)$$

Sixth Stage

$$\frac{dA_6}{dt} = \frac{Q}{V}(A_5 - A_6) - K_1 \cdot A_6/(K_{ss} + A_6)$$

$$\frac{dB_6}{dt} = \frac{Q}{V}(B_5 - B_6) + K_1 \cdot A_6/(K_{ss} + A_6) - K_2 \cdot B_6/(K_{sb} + B_6)$$

$$\frac{dC_6}{dt} = \frac{Q}{V}(C_5 - C_6) + K_2 \cdot B_6/(K_{sb} + B_6)$$

where A_i = ammonia concentration at ith stage, mg/ℓ

B_i = nitrite concentration at ith stage, mg/ℓ

C_i = nitrate concentration at ith stage, mg/ℓ

K_{ss} = half-saturation coefficient for Nitrosomonas, mg/ℓ

K_{sb} = half-saturation coefficient for Nitrobacter, mg/ℓ

K_1 = rate coefficient for ammonia oxidation, mg/ℓ · hr

K_2 = rate coefficient for nitrite oxidation, mg/ℓ · hr

The above equations were solved numerically by the use of the Continuous System Modeling Program, available in the IBM library package.

The results were calculated for the series of flow loading values used and recorded in Appendix A (Tables A-1 through A-11). The kinetic factors are shown in Table 22 below.

TABLE 22. CALCULATED KINETIC COEFFICIENTS FROM SALINE PILOT PLANT

Flow loading, gpd/ft^2	Detention time per stage		Units	
	min	hr	K_1, mg/ℓ · hr	K_{ss}, mg/ℓ
0.25	156.6	2.666	12	8
1.00	39.0	0.660	30	10
2.00	19.5	0.330	45	15
2.50	15.6	0.260	60	18
3.00	12.9	0.216	60	18
4.00	9.7	0.163	60	18
6.00	6.5	0.108	60	18

The similarity between these data and the values reported in Table 7, page 34, are striking. Obviously, the region of underloading which was roughly assumed to terminate somewhere above 1.0 gpd/ft^2 (40.7 ℓ/m^2/day) appears to extend to 2.0 gpd/ft^2 (81.4 ℓ/m^2/day). Above this point the kinetic coefficients appear to be uniform. Figures 27 and 28 show the rather excellent correlation between predicted and observed ammonia profiles at the selected steady state flow loading values.

It should be recognized that the K_{ss} values as defined by this technique are substantially higher than those reported in the literature for suspended growths of Nitrosomonas, either as a pure culture or in activated sludge. This circumstance is judged to be an indication of diffusional resistances developing as the biological films increase in thickness.

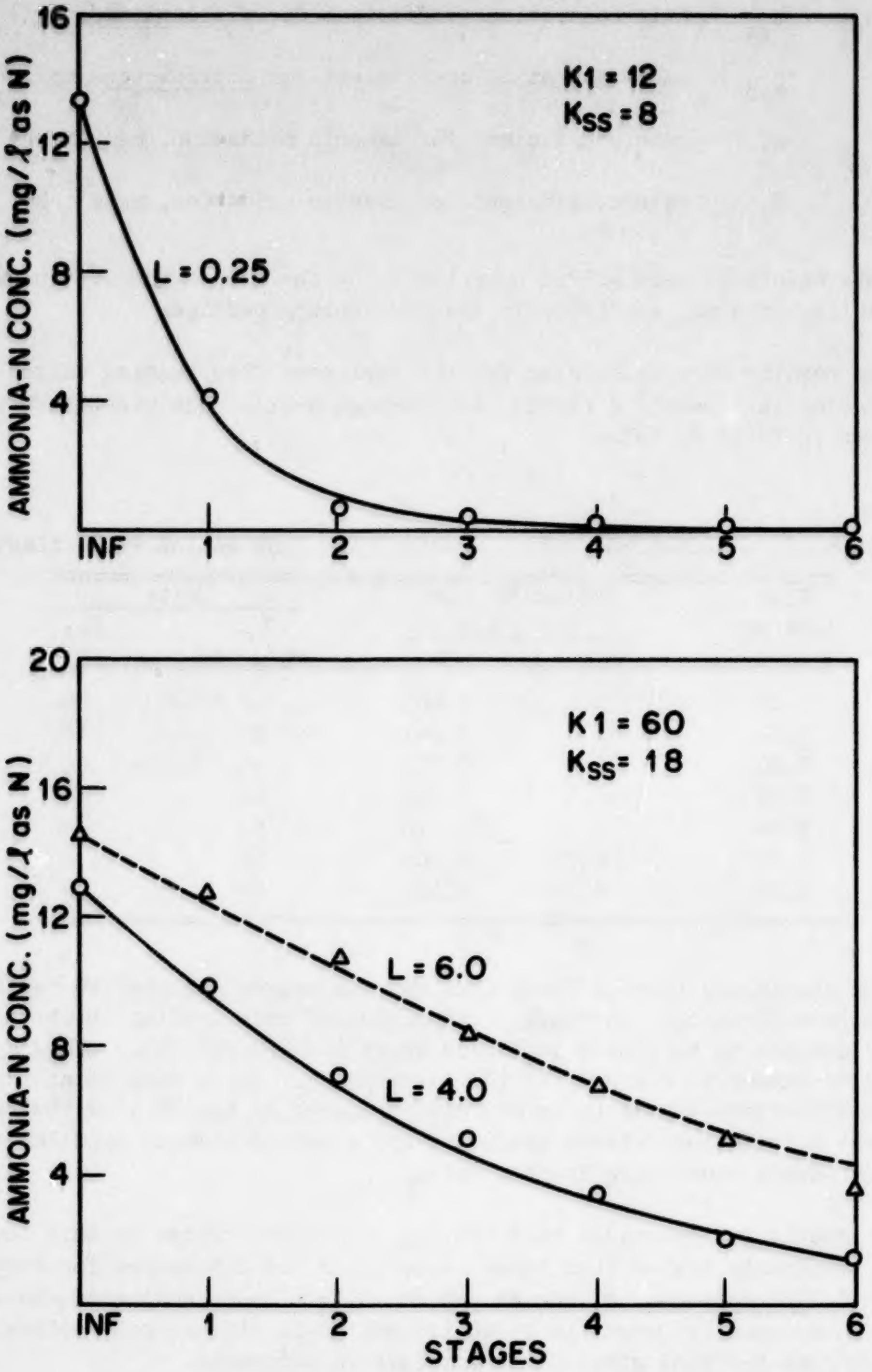

Figure 27. Comparison of predicted and observed ammonia profiles at steady state.

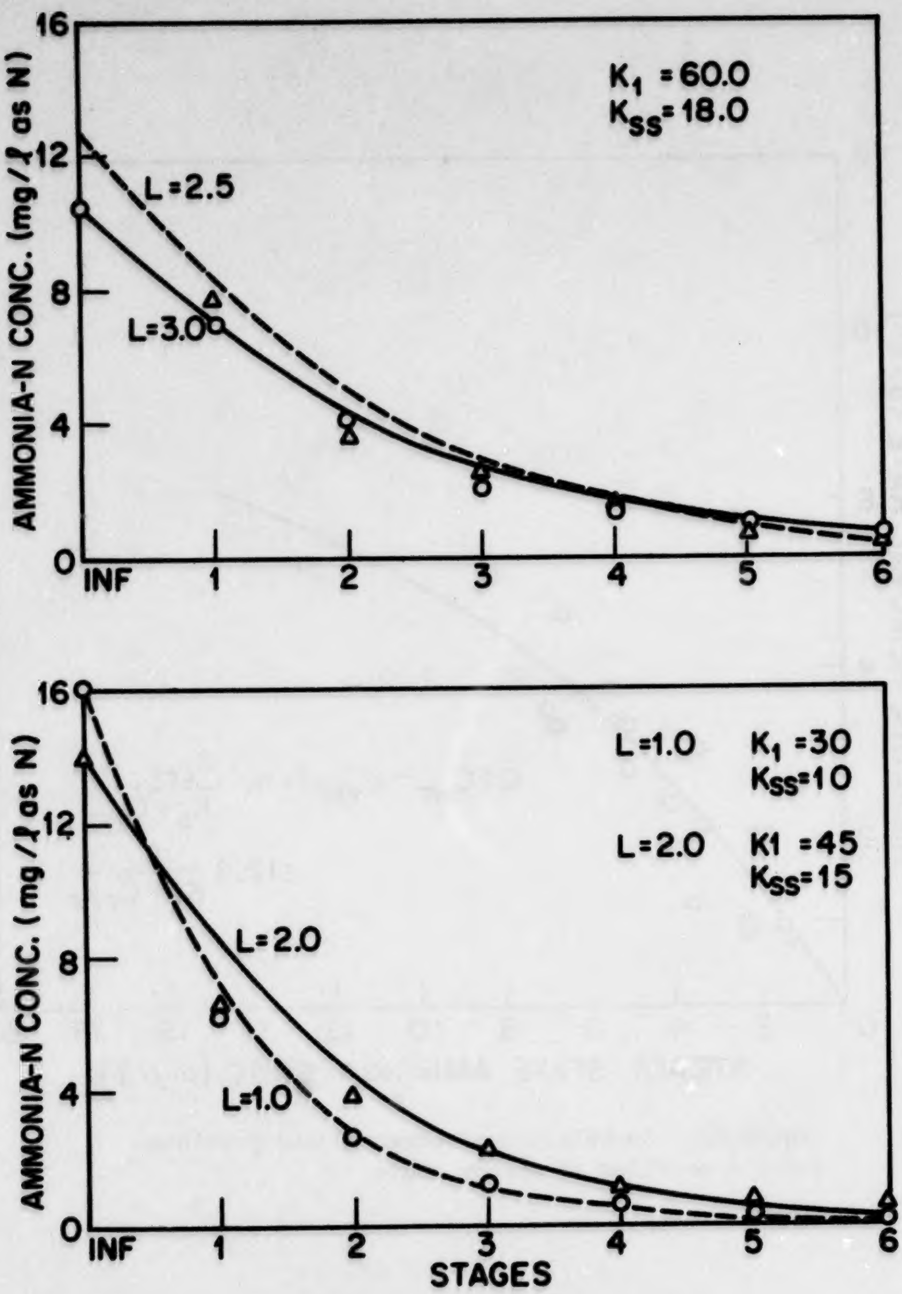

Figure 27. (Concluded)

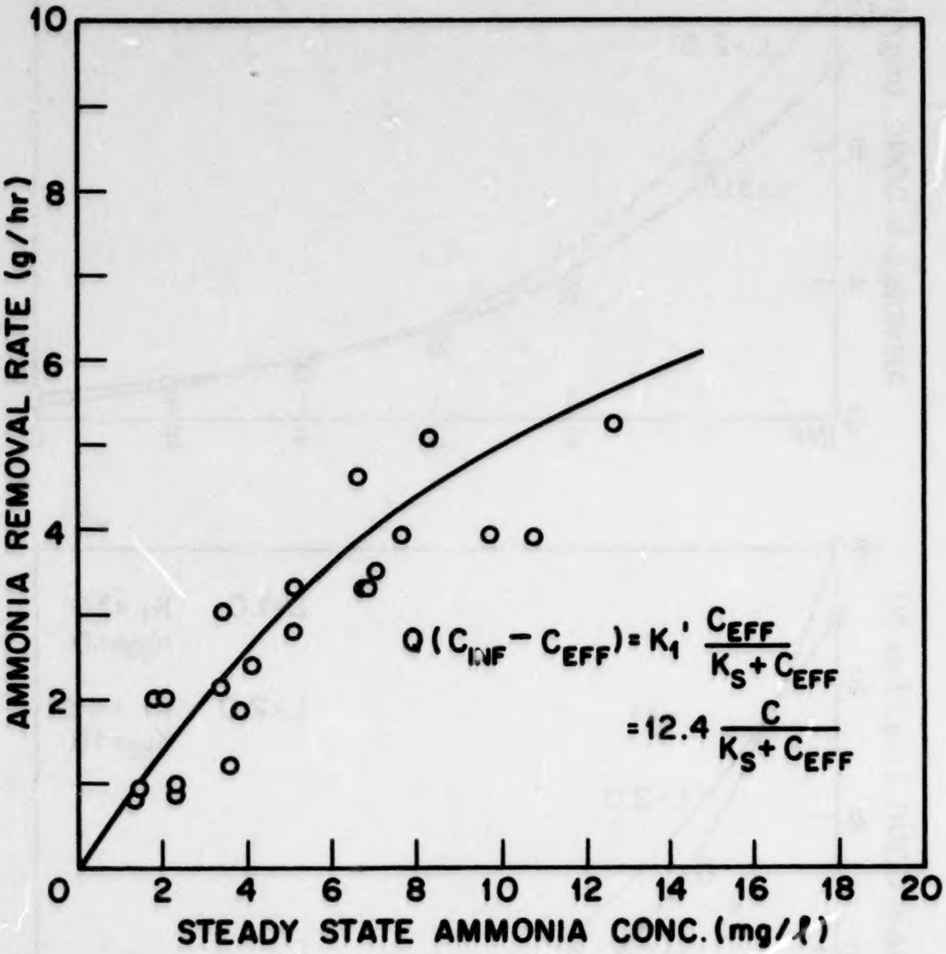

Figure 28. Correlation of observed and predicted ammonia profiles at steady state.

Once the unit is fully stabilized, the data may be treated in the following fashion:

$$Q(C_{inf} - C_{eff}) = K_1 \frac{C_{eff}}{K_{ss} + C_{eff}} \cdot V = K_1' \frac{C_{eff}}{K_{ss} + C_{eff}}$$

where $K_1' = \frac{K_1 \cdot V}{1000} = 12.4$

The curve representing this equation is shown in Figure 28. Twenty-two data points were selected from Table 9 as being representative of a fully stabilized condition. These points are superimposed on the curve of Figure 28 and indicate excellent agreement. Obviously the completed curve will require additional flow loading data at higher values.

The level of substrate actually available to the average nitrifying organisms in the film is considerably less than the level in the bulk liquid. It probably can be estimated as being the bulk concentration divided by the K_{ss} but at the present time, it can only be chosen indirectly.

To be fully predictive this kinetic model needs further elaboration. X and μ_{max} are assumed to be constants once the RBS system has reached steady state. These quantities to date have not been measurable directly (as has been noted). However, if these two terms are constants and the A/V term is likewise constant for a given system, the K_1 must be directly proportional to the Nitrosomonas concentration. Further study of the bio-film will be necessary to elaborate this premise.

On the basis of the above facts, it would be ill advised to extend the use of this model to other systems dissimilar in substrate composition, area to volume ratios, varying proportions of heterotrophs and alkalinity or pH differences.

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APPENDIX A. NITROGEN DATA—SALINE

TABLE A-1. NITRIFICATION DATA FLOW LOADING = 0.25 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
8/02	1.4	21.0	9.4	6.6	0.7	12.4	0.4	13.5	0.2	13.5	0.4	13.5	0.2	13.5	0.4	13.5
8/20	0.8	21.0	11.0	4.1	0.2	23.0	0.2	23.0	0.2	22.5	0.2	22.5	0.2	22.5	0.2	22.0
8/21	0.8	22.0	10.0	3.1	0.2	14.0	0.2	14.0	0.2	14.0	0.2	14.0	0.2	14.0	0.2	14.0
8/26	1.8	22.5	14.4	3.0	1.9	14.0	1.4	14.0	1.4	14.0	0.9	13.6	0.5	14.4	0.5	14.0
8/28	1.7	21.0	16.2	2.8	2.5	10.8	1.9	12.4	1.0	14.0	1.0	15.2	0.6	13.6	0.6	13.6
8/29	0.7	23.0	12.4	2.6	1.2	10.0	0.8	10.4	0.5	11.0	0.2	12.0	0.5	12.0	0.4	11.5
9/04	0.8	21.0	12.4	2.5	0.8	10.4	0.8	10.4	0.2	10.4	0.2	10.4	0.2	10.4	0.2	10.4
9/09	1.5	19.0	11.8	2.2	0.6	10.1	0.5	10.1	0.2	10.5	0.3	11.0	0.8	11.0	0.8	11.0
9/11	1.0	20.0	11.7	1.5	1.2	10.0	0.6	11.6	0.7	11.6	0.6	11.8	0.6	11.6	0.7	11.6
9/12	0.8	20.0	14.0	0.6	0.9	11.2	0.7	11.2	0.9	11.2	0.8	12.0	0.5	12.0	0.4	11.6
9/16	1.3	19.0	13.5	0.9	1.0	12.2	0.6	12.8	0.4	13.4	0.3	14.6	0.3	12.8	0.2	12.8
9/18	1.3	20.0	11.8	0.2	1.0	11.2	1.0	12.5	0.8	12.9	0.7	13.8	0.6	13.2	0.6	13.0
9/29	1.8	17.0	13.0	4.3	0.7	16.2	0.9	16.2	0.7	15.2	0.7	16.1	0.6	16.1	0.9	15.8
10/01	1.8	18.0	14.4	2.1	0.8	15.2	0.7	16.0	0.5	15.0	0.3	15.1	0.3	15.8	0.7	14.6
10/06	1.2	17.0	13.2	7.5	13.5	9.2	0.2	24.0	0.1	24.0	0.1	24.0	0.1	22.6	0.1	22.6
10/08	1.0	17.0	19.2	3.8	16.6	2.4	0.3	17.8	0.1	18.8	0.1	17.4	0.1	17.8	0.2	17.8
10/10	1.0	17.0	14.5	4.6	13.5	4.4	0.4	22.7	0.3	23.2	0.1	23.1	0.2	23.9	0.3	23.1
10/13	1.9	17.8	12.9	4.6	9.4	5.2	0.4	18.8	0.3	21.2	0.3	18.8	0.3	20.6	0.3	18.7
10/15	1.5	19.0	19.3	9.6	11.0	10.9	0.5	20.8	0.1	20.8	0.1	20.8	0.1	20.8	0.1	20.8
$\bar{x}$	1.3		13.4	4.2	4.1	11.2	0.7	15.4	0.5	15.6	0.4	15.8	0.4	15.7	0.4	15.4

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of (NO_3 + NO_2) mg/ℓ as N.

TABLE A-2. NITRIFICATION DATA FLOW LOADING = 0.5 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
10/17	2.8	15.5	12.0	4.3	12.0	4.4	1.3	15.4	0.4	16.8	0.3	16.5	0.1	16.5	0.1	15.8
10/20	2.8	16.2	9.4	5.5	11.4	5.8	0.6	20.5	0.4	18.4	0.4	17.0	0.3	19.4	0.4	18.7
10/22	2.8	18.0	13.5	4.4	--	--	1.0	14.4	0.4	20.1	0.3	20.7	0.3	20.5	0.2	20.4
10/24	2.6	17.0	11.0	11.0	0.9	20.5	0.2	22.2	0.2	22.5	0.2	23.0	0.2	25.0	0.2	25.0
10/27	1.5	15.0	14.0	12.1	0.4	24.0	5.4	23.5	0.4	27.0	0.4	27.9	0.4	28.9	0.4	26.7
10/29	2.8	16.0	20.0	6.0	1.0	9.4	0.6	18.0	0.4	18.0	0.4	18.0	0.4	18.0	0.4	18.0
10/31	2.0	13.5	14.0	3.7	6.8	13.8	5.0	10.5	0.2	16.3	0.2	16.5	0.3	16.7	0.2	17.2
11/03	2.8	18.0	19.0	15.1	1.6	24.8	0.8	24.8	0.4	31.2	0.3	31.4	0.3	32.0	0.2	32.0
11/05	3.0	18.5	12.6	5.3	1.4	14.4	0.7	15.2	0.2	13.8	0.2	15.5	0.2	15.8	0.1	15.8
11/07	2.8	18.8	14.6	4.6	7.4	18.3	7.3	13.4	0.4	17.2	0.2	17.7	0.3	17.8	0.3	17.5
$\bar{x}$	2.6	16.7	14.0	7.2	4.3	15.0	1.3	17.8	0.3	20.1	0.3	20.4	0.3	21.1	0.3	20.7

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of $(NO_3 + NO_2)$ mg/ℓ as N.

TABLE A-3. NITRIFICATION DATA FLOW LOADING = 1.0 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
11/19	4.73	16.0	15.5	4.7	1.3	21.0	5.4	18.6	0.3	26.0	0.3	26.3	0.2	24.5	0.2	25.7
12/10	4.73	11.5	19.7	5.9	2.2	9.9	0.9	15.8	0.4	18.0	0.3	18.1	0.3	18.0	0.1	18.5
12/19	4.73	--	12.8	1.8	1.8	10.8	0.9	13.2	0.5	10.6	0.1	9.0	0.1	10.2	0.5	13.4
12/22	4.00	8.5	15.9	6.2	1.8	16.8	0.9	16.8	0.3	14.0	0.2	16.0	0.1	17.0	0.2	16.0
12/24	4.25	8.0	12.2	7.4	1.0	15.0	0.5	16.6	0.5	16.4	0.4	16.2	0.3	16.6	0.1	16.6
12/26	4.73	8.5	16.0	1.4	2.0	13.4	0.7	14.4	0.5	14.8	0.4	14.8	0.3	14.0	0.6	14.6
12/29	5.40	8.5	16.7	5.6	2.6	14.0	1.0	15.6	0.6	13.4	0.4	16.2	0.3	16.0	0.2	16.0
12/31	5.68	9.0	14.4	4.5	1.7	15.0	1.0	15.7	0.3	16.2	0.3	17.3	0.2	17.5	0.1	18.0
1/02	--	8.0	14.5	5.4	2.2	15.0	1.0	15.3	3.2	15.0	0.3	16.5	0.2	16.0	0.1	16.7
1/05	--	8.0	13.4	3.6	2.6	9.0	1.0	9.5	0.5	9.3	0.2	10.2	0.2	10.7	0.1	10.8
1/07	5.41	8.5	15.8	3.3	3.4	9.6	1.8	9.3	1.0	10.2	0.8	10.4	0.3	10.8	0.1	11.4
1/12	4.73	9.5	15.0	4.1	10.8	11.0	1.1	12.5	0.5	11.7	0.4	11.9	0.2	10.5	0.1	13.0
1/14	4.73	10.0	16.0	1.8	--	--	0.8	12.4	0.3	15.5	0.5	15.5	0.1	15.7	0.1	16.1
1/16	4.73	10.0	15.0	1.5	5.1	13.2	1.0	10.6	0.6	11.2	0.5	12.2	0.4	12.0	0.1	12.9
1/21	5.40	9.5	16.4	1.6	10.2	9.5	4.0	9.8	1.7	10.6	0.9	10.3	0.5	10.0	0.5	11.0
1/23	4.73	9.0	18.0	1.9	13.0	10.4	8.6	11.3	3.5	12.0	1.0	13.6	0.6	13.0	1.0	13.2
1/26	4.73	10.5	22.2	5.6	11.2	11.4	11.4	12.3	3.2	16.2	2.6	16.0	1.4	15.6	1.4	17.0
1/28	4.73	9.5	19.4	2.2	9.6	9.0	5.0	10.5	1.2	10.5	1.0	11.8	0.6	10.5	0.4	11.4
1/30	4.73	10.0	16.4	1.8	8.8	9.4	5.1	11.5	1.3	11.4	0.7	11.8	0.4	12.0	0.1	12.5
2/02	4.73	7.0	12.8	7.3	6.3	11.5	2.8	11.8	1.1	12.7	1.1	13.8	0.7	13.5	0.2	14.5
2/04	4.73	10.2	19.8	3.7	9.5	12.7	3.9	13.2	1.6	12.6	0.4	15.2	0.4	15.3	0.3	14.8
2/06	4.73	10.2	19.6	2.5	5.4	12.4	2.5	13.8	0.7	14.2	0.8	12.3	0.3	13.8	0.2	14.9
$\bar{x}$	4.81	--	16.3	3.9	5.4	12.4	2.8	11.0	1.1	13.8	0.6	14.3	0.4	14.2	0.3	15.0

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of (NO_3 + NO_2) mg/ℓ as N.

TABLE A-4. NITRIFICATION DATA FLOW LOADING = 1.5 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
2/09	7.57	--	17.4	2.9	3.9	14.0	1.4	13.8	0.6	13.4	0.4	13.9	0.4	12.3	0.2	15.1
2/11	7.57	11.5	16.4	1.8	5.0	8.6	3.3	11.6	2.0	12.6	0.8	13.0	0.7	13.6	0.4	14.4
2/13	--	11.5	15.0	1.3	7.6	7.3	2.6	7.9	1.0	8.6	0.6	9.6	0.4	8.5	0.5	9.2
2/16	7.57	--	9.1	1.0	3.9	6.2	2.7	6.5	0.8	5.6	0.4	7.5	0.1	6.0	0.2	7.0
2/20	7.57	12.5	9.7	1.3	3.1	5.7	1.6	6.8	--	--	0.3	7.6	0.2	7.0	0.2	7.4
2/23	7.57	10.5	5.4	1.2	2.8	7.0	0.8	8.0	0.3	7.7	0.9	8.1	0.1	8.1	0.1	9.2
2/25	7.57	13.0	10.0	1.5	1.7	8.0	0.6	9.9	0.3	8.2	0.2	9.3	0.2	9.7	0.1	10.5
2/27	6.30	13.0	11.4	3.2	1.9	8.4	0.5	9.0	0.4	8.7	0.4	9.8	0.3	8.8	0.4	9.5
3/01	5.40	11.6	10.0	3.3	1.3	10.5	0.4	12.5	0.4	12.5	0.3	11.6	0.2	9.2	0.2	12.8
3/03	5.40	11.0	6.8	2.1	0.2	5.8	0.2	6.0	0.2	5.5	0.2	6.0	0.2	5.3	0.2	6.0
$\bar{x}$	--	--	12.3	2.0	3.3	5.0	1.7	6.5	0.8	7.1	0.4	7.6	0.3	7.8	0.2	8.9

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of $(NO_3 + NO_2)$ mg/ℓ as N.

TABLE A-5. NITRIFICATION DATA FLOW LOADING = 2.0 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
3/10	10.8	11.0	11.2	1.0	6.4	7.0	5.2	8.1	3.1	8.8	1.7	10.5	1.0	10.3	0.6	11.1
3/12	10.8	11.0	12.4	1.2	8.0	6.2	5.5	8.6	2.9	9.6	1.9	10.6	1.1	10.9	0.8	11.2
3/15	10.8	11.5	9.8	1.2	4.9	7.3	2.7	9.0	1.3	10.1	0.8	10.5	0.5	11.5	0.3	11.9
3/17	10.8	10.0	11.7	2.4	8.0	5.1	5.3	7.5	2.8	9.1	1.9	10.2	0.8	10.4	0.8	10.6
3/19	9.5	14.0	15.6	1.6	10.3	5.7	8.0	6.6	5.2	8.2	1.9	9.4	0.9	9.6	0.7	10.1
3/26	9.1	15.0	10.5	0.8	3.1	8.6	--	--	--	--	0.9	8.4	0.5	8.6	0.3	9.5
3/29	8.7	13.0	10.0	2.3	1.3	11.2	0.7	10.2	0.8	10.0	0.3	11.1	0.3	11.0	0.2	11.8
4/05	9.5	14.0	15.0	8.3	5.3	22.0	2.7	19.5	1.4	23.0	1.0	20.6	0.6	20.0	0.4	25.2
4/07	7.3	15.0	12.2	2.3	1.9	9.1	0.8	9.0	0.8	9.0	0.5	9.0	0.8	10.2	0.2	11.1
4/16	10.8	17.0	19.0	2.5	2.8	12.2	0.4	14.2	0.4	14.4	0.3	14.5	0.3	16.3	0.2	16.5
4/19	10.8	17.0	--	--	10.0	17.8	5.8	28.6	3.4	26.8	2.8	27.9	2.4	29.5	2.2	30.3
4/21	10.8	15.0	16.1	2.1	5.9	9.8	2.3	9.7	1.8	10.9	1.0	12.5	0.5	13.0	0.4	13.4
4/28	9.5	14.0	12.4	3.0	1.6	10.8	0.3	11.9	0.3	12.6	0.2	12.1	0.1	12.2	0.1	12.7
4/30	10.3	14.0	15.6	5.6	8.0	12.3	2.6	14.4	1.4	15.9	0.9	16.6	0.5	17.4	0.4	18.6
5/03	8.7	14.0	18.8	2.7	7.6	10.0	--	--	2.4	10.9	1.8	14.2	1.6	15.2	1.4	15.5
$\bar{x}$	9.9	--	13.6	2.7	5.7	8.9	3.5	12.1	2.0	12.8	1.2	13.2	0.8	13.7	0.6	14.5

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of $(NO_3 + NO_2)$ mg/ℓ as N.

TABLE A-6. NITRIFICATION DATA FLOW LOADING = 2.5 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
5/10	15.0	11.7	8.6	3.5	2.8	12.6	1.3	12.6	0.9	12.3	0.4	12.7	0.3	14.1	0.2	14.8
5/14	16.0	16.5	13.8	3.1	9.6	10.0	8.3	11.5	4.2	11.6	3.8	11.7	1.4	14.3	1.0	14.6
5/19	16.0	14.9	10.1	2.2	7.2	7.6	5.7	8.7	3.5	9.7	2.3	11.4	1.6	11.6	1.3	12.0
5/21	18.0	14.9	12.2	1.1	7.4	7.6	4.5	9.1	2.2	9.9	1.6	11.4	0.7	11.8	0.5	11.4
5/24	15.0	12.5	11.4	6.5	6.4	12.8	3.0	14.1	1.1	15.4	1.0	15.9	0.5	16.5	0.3	16.0
5/28	17.5	11.3	12.8	6.6	7.1	11.8	2.4	16.0	0.6	18.4	0.5	18.6	0.3	19.0	0.3	18.4
6/01	18.0	12.0	14.2	3.4	8.6	9.2	2.8	15.1	0.6	15.9	0.5	17.4	0.3	17.5	0.2	17.9
6/07	18.0	13.3	14.4	1.3	7.0	7.5	2.9	11.1	0.8	12.6	0.5	13.2	0.3	13.2	0.2	13.8
$\bar{x}$	--	13.2	12.2	3.4	7.0	9.9	3.9	12.3	1.7	13.2	1.3	14.0	0.7	14.7	0.5	14.8

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of $(NO_3 + NO_2)$ mg/ℓ as N.

TABLE A-7. NITRIFICATION DATA FLOW LOADING = 3.0 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
6/16	16.0	18.0	15.8	3.7	13.0	6.2	9.6	10.5	6.3	12.1	4.6	14.5	4.5	15.2	3.2	15.8
6/18	13.3	19.5	13.8	11.0	5.2	17.4	4.0	19.0	1.1	23.0	0.7	24.2	0.4	24.5	0.3	24.5
6/21	16.0	18.0	21.5	1.7	20.8	2.8	17.3	6.3	10.2	11.8	9.7	12.4	7.3	13.8	5.0	17.2
6/23	16.0	18.0	13.5	1.7	11.3	3.3	9.0	5.8	4.4	12.0	2.9	13.1	2.0	13.6	1.8	13.8
6/25	16.0	19.5	8.0	2.1	5.6	4.8	4.8	6.3	1.3	9.4	0.9	9.4	0.3	9.7	0.1	9.7
6/30	13.3	--	8.9	0.1	6.4	1.2	1.5	0.9	0.5	0.3	0.4	0.1	0.2	0.1	0.1	0.1
7/02	16.0	17.0	10.5	10.8	6.5	14.4	2.3	17.8	0.6	19.9	0.5	20.1	0.5	20.7	0.2	21.6
7/05	16.0	19.0	6.9	3.0	3.5	7.0	1.3	10.1	0.4	11.5	0.2	11.7	0.2	12.0	0.1	12.2
7/08	16.0	21.0	10.1	3.5	6.9	7.1	2.7	11.2	0.6	13.9	0.3	14.4	0.2	14.8	0.1	15.0
7/19	15.4	19.0	9.6	3.6	3.7	10.5	1.4	14.0	0.5	15.7	0.3	16.2	0.3	15.5	0.1	16.0
7/21	15.4	20.5	7.6	3.3	4.2	7.4	2.0	10.5	0.9	11.9	0.8	11.8	0.6	12.4	0.4	12.6
$\bar{x}$	15.4	--	10.6	4.7	6.7	8.7	4.1	11.7	1.8	14.4	1.2	15.0	1.0	15.4	0.7	15.7

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of (NO_3 + NO_2) mg/ℓ as N.

TABLE A-8. NITRIFICATION DATA FLOW LOADING = 4.0 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
7/30	1.6	20.0	17.8	2.8	14.2	6.3	10.8	10.0	6.6	14.5	4.7	16.6	3.7	17.5	2.6	18.5
8/02	1.6	18.0	7.7	2.6	5.6	5.0	3.2	7.0	2.6	8.7	2.0	9.6	1.0	10.6	0.8	10.9
8/06	1.6	19.0	11.4	2.3	7.4	6.1	5.1	8 2	3.8	9.7	2.7	10.0	1.6	10.8	1.2	11.0
8/09	1.6	18.0	8.4	8.0	5.7	10.3	3.6	12.8	2.0	13.0	1.8	13.4	0.8	14.2	0.6	14.8
8/11	1.6	20.0	15.5	--	13.0	--	10.3	--	8.2	--	5.6	--	2.0	--	1.1	--
8/13	--	22.0	16.2	3.4	12.6	5.0	10.0	5.4	9.1	6.4	5.2	7.4	3.4	9.6	3.0	--
8/16	1.6	20.0	12.5	3.8	9.0	5.0	6.2	8.0	3.0	10.3	1.8	12.3	1.1	12.8	0.7	13.5
8/18	1.6	19.0	11.0	1.7	8.0	3.8	5.8	4.7	5.7	5.0	2.8	6.8	2.0	8.0	1.0	10.0
8/23	1.4	20.0	11.0	--	10.3	4.7	8.0	5.4	5.8	6.6	6.4	8.0	4.1	9.0	2.4	9.4
8/25	1.6	--	13.3	--	10.8	4.2	10.1	6.7	7.5	8.2	7.2	9.3	5.7	11.4	3.7	--
$\bar{x}$	1.6	--	12.5	3.4	9.8	5.7	7.4	7.8	5.5	8.4	4.0	9.3	2.6	11.8	1.7	12.7

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of (NO_3 + NO_2) mg/ℓ as N.

TABLE A-9. NITRIFICATION DATA FLOW LOADING = 5.0 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
9/03	27.7	19.5	13.0	5.7	12.8	7.6	10.7	8.3	8.6	8.8	7.0	10.2	5.4	11.5	4.2	12.5
9/07	27.7	20.5	17.0	5.7	14.1	7.0	11.6	7.8	9.6	9.5	7.7	10.0	5.6	11.5	4.7	12.0
9/08	27.7	20.5	20.0	1.5	17.6	2.7	15.3	4.1	13.0	4.7	10.0	6.8	7.5	8.8	5.0	10.0
9/10	27.7	18.0	17.6	4.1	16.4	5.2	14.0	6.3	12.1	9.9	10.5	10.0	8.6	12.5	7.0	13.0
9/13	27.7	20.0	16.6	5.1	16.0	5.8	15.0	6.3	13.2	9.0	10.6	9.5	8.0	11.5	6.1	14.0
9/15	27.7	20.0	26.9	2.6	25.4	5.0	24.4	4.8	22.8	5.6	20.4	6.4	18.4	8.0	14.8	11.2
$\bar{x}$	--	--	18.5	4.1	17.0	5.4	15.2	5.8	13.2	6.5	11.0	7.1	8.9	7.8	7.0	8.5

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of $(NO_3 + NO_2)$ mg/ℓ as N.

TABLE A-10. NITRIFICATION DATA FLOW LOADING = 6.0 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
9/17	32.4	19.5	20.0	5.8	18.4	6.8	16.5	9.6	14.6	11.2	12.5	13.0	11.4	14.0	9.4	14.6
9/20	30.7	19.5	12.7	2.4	11.5	3.5	9.3	6.0	7.8	7.5	6.8	8.1	5.0	9.4	3.4	10.2
9/23	--	17.5	13.8	5.5	12.1	6.8	10.1	8.2	8.0	10.3	6.5	11.9	4.7	12.8	2.8	14.2
9/27	--	17.0	10.0	3.5	8.8	4.9	7.2	6.0	4.5	8.6	3.3	9.6	1.3	10.8	0.9	11.0
9/29	31.5	17.0	11.0	5.5	9.0	8.1	6.6	10.5	4.0	12.4	2.1	14.1	1.0	14.6	0.7	15.0
10/01	31.5	17.0	9.9	5.5	7.5	7.2	5.5	9.0	3.1	10.5	1.7	12.4	0.7	12.5	0.5	13.3
10/05	31.5	19.0	19.5	4.2	16.0	7.5	14.1	9.7	11.8	10.6	9.9	11.5	8.2	13.0	7.0	14.3
10/07	--	--	13.5	5.7	11.5	10.4	11.3	11.0	7.1	5.8	7.5	13.9	5.2	15.9	2.0	11.0
10/13	31.5	17.0	10.3	5.9	7.1	8.6	5.7	9.9	2.5	12.1	1.4	13.0	0.6	13.2	0.4	13.9
10/14	32.4	14.5	8.9	7.4	6.5	9.3	4.2	10.9	2.1	11.3	1.0	13.0	0.5	14.5	0.4	14.5
10/15	31.5	16.5	16.9	8.7	13.8	10.5	11.0	11.8	8.3	13.9	6.2	15.9	3.7	18.5	2.2	20.9
10/19	--	--	12.6	3.2	6.8	9.2	6.2	9.9	3.5	12.2	2.0	12.5	1.0	14.4	1.1	12.0
10/20	30.7	13.5	12.1	3.7	7.6	6.6	7.2	8.5	4.3	10.9	2.7	12.1	1.1	13.4	0.9	13.7
10/21	29.8	13.0	16.0	2.6	14.8	4.5	14.1	5.4	11.2	7.5	9.5	8.6	5.9	12.6	4.8	13.6
10/22	30.7	12.0	18.6	1.2	15.1	4.7	11.9	6.0	8.5	7.5	6.0	8.3	3.3	10.5	1.8	14.4
10/25	--	--	18.6	3.6	17.3	4.9	17.0	5.2	14.5	7.2	13.5	8.3	12.1	10.2	10.3	10.8
10/26	34.4	15.0	16.2	2.2	14.8	3.8	12.2	8.0	9.9	9.2	9.0	8.0	6.8	9.5	4.8	12.7
10/27	33.4	16.0	15.1	1.5	--	5.3	10.5	6.0	8.2	7.5	7.8	8.3	6.0	9.3	3.7	10.6
10/29	33.4	14.0	24.1	2.0	19.0	3.1	18.9	4.6	15.6	8.3	15.5	9.0	12.7	10.6	10.6	12.8
11/01	33.4	15.0	24.1	1.5	22.9	3.2	15.7	9.0	13.9	10.7	11.5	11.5	12.4	14.7	5.8	14.8
$\bar{x}$	31.9	16.1	14.3	4.1	13.4	6.4	10.8	8.3	8.2	9.8	6.8	11.2	5.8	12.7	3.7	13.4

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of $(NO_3 + NO_2)$ mg/ℓ as N.

TABLE A-11. NITRIFICATION DATA FLOW LOADING = 3.5 gpd/ft^2 - 4-ft dia

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
11/22	23.3	13.0	15.2	3.0	14.9	4.5	14.8	5.5	10.2	8.0	8.2	9.3	5.3	11.6	4.3	13.0
11/30	23.3	--	13.9	8.5	15.8	4.3	8.7	10.7	5.7	12.3	2.8	15.5	1.1	16.3	0.9	17.3
11/30	14.9	10.0	18.7	5.7	12.0	10.5	8.6	11.9	5.3	15.5	2.7	17.4	1.2	17.7	0.8	18.4
12/01	9.5	11.0	25.8	3.5	17.5	8.9	14.5	10.7	9.3	13.8	5.4	16.8	2.2	19.4	0.8	15.4
12/01	20.4	11.0	24.1	2.6	22.7	3.9	20.5	4.7	18.0	6.0	15.7	7.4	13.5	8.8	12.9	9.6
12/02	18.6	8.0	20.0	2.9	13.8	11.9	15.1	6.4	9.0	10.7	5.9	12.6	3.1	14.2	2.0	15.0
12/03	18.3	7.5	16.7	4.4	13.6	6.0	12.1	6.9	9.8	8.6	7.8	10.4	5.5	12.2	4.8	12.8
12/04	18.3	11.0	11.8	4.4	6.1	6.7	5.2	7.8	2.8	10.2	2.7	12.0	1.7	14.4	2.4	15.6
12/05	18.3	12.0	16.7	4.0	12.5	6.8	10.3	8.4	6.9	11.5	5.0	14.2	2.0	17.0	1.6	18.1
12/06	18.3	12 0	20.1	3.5	13.3	8.5	7.8	10.5	3.7	13.0	1.5	15.0	0.7	15.5	0.5	15.7
12/09	18.0	11.0	21.5	3.7	16.3	6.3	13.9	8.0	10.8	8.3	7.6	11.5	5.4	13.5	4.5	13.7
12/09	18.3	11.0	20.2	2.3	19.8	4.0	16.6	4.7	13.5	6.6	11.0	8.2	8.3	9.8	8.1	11.4
12/10	18.3	10.0	20.1	2.6	18.2	4.2	17.0	5.0	13.8	7.2	-1.7	8.6	8.5	11.0	6.8	12.1
12/12	18.3	10.0	20.2	4.2	16.4	6.7	15.0	8.4	12.0	10.3	9.8	12.0	6.2	15.0	4.6	17.3
12/13	18.3	8.0	31.3	19.0	28.5	23.5	27.3	25.7	25.3	27.2	22.5	28.5	19.0	37.0	16.8	39.0
12/13	14.5	7.0	25.5	12.0	25.8	12.9	25.1	14.2	23.0	16.5	22.1	20.3	19.5	25.7	18.4	26.8
12/14	18.9	8.0	29.5	3.0	23.3	4.3	20.5	5.4	16.9	7.7	18.1	8.8	10.5	11.4	9.1	12.5
12/14	18.3	10.0	25.6	4.6	25.0	4.5	24.0	5.1	19.2	7.4	16.5	9.4	12.7	11.4	10.7	12.8
12/15	18.9	11.0	17.9	2.9	14.1	4.9	12.5	6.1	9.3	8.7	7.2	10.2	4.3	13.0	2.7	14.0
12/16	18.3	11.0	20.5	3.2	17.0	5.4	14.6	6.5	11.3	9.8	8.8	11.4	4.8	14.2	2.9	16.9
12/17	18.3	12.0	22.0	3.2	16.4	6.1	14.4	8.0	10.7	11.1	7.5	11.5	3.4	14.5	2.1	15.0
12/18	18.3	12.0	20.0	2.7	14.5	5.7	12.3	7.5	8.8	10.8	6.0	11.5	2.3	14.2	1.2	15.5
12/19	18.3	12.0	13.9	4.6	10.1	7.8	8.0	9.5	5.4	12.5	2.2	12.9	1.0	13.5	0.6	14.2

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of $(NO_3 + NO_2)$ mg/ℓ as N.

TABLE A-11. (Concluded)

Date	Flow, ℓ/min	Temp., °C	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
			NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
12/20	18.3	12.0	26.1	4.4	17.5	8.2	14.0	10.2	9.7	13.5	6.2	13.9	2.5	15.4	1.2	17.5
12/24	18.6	9.0	23.2	26.2	15.5	3.0	13.0	31.8	8.6	34.0	4.5	38.1	1.9	39.6	1.2	42.1
12/29	18.3	9.0	15.1	4.8	9.1	9.6	6.5	11.8	2.7	14.8	1.5	15.5	0.7	16.2	0.4	15.7
12/29	16.2	9.0	24.0	5.5	12.9	10.5	10.4	12.4	5.9	15.6	2.5	17.2	0.9	18.2	0.6	18.8
1/05	14.2	10.0	16.8	6.2	9.9	12.0	7.0	13.8	2.6	17.1	1.1	17.9	0.6	18.8	0.5	19.1
1/02	18.0	9.5	23.2	2.4	20.6	4.6	20.8	5.9	16.8	8.2	14.6	10.4	12.0	12.8	9.9	14.4
1/25	18.9	10.0	20.2	1.4	16.9	3.7	14.2	5.1	12.9	7.9	9.2	9.7	6.1	12.9	4.0	15.0
1/26	18.6	--	20.2	1.7	15.4	4.9	13.6	6.4	10.0	9.0	7.8	11.0	5.2	14.6	2.3	16.2
1/27	16.7	7.0	22.0	8.0	19.8	10.7	18.4	12.4	15.4	15.6	13.0	18.2	9.2	20.5	7.5	21.7
2/05	18.0	7.0	20.2	2.1	17.8	3.7	16.6	4.8	13.2	7.1	10.5	9.1	6.1	11.6	3.7	13.5
$\bar{x}$	18.5	9.4	20.7	5.3	16.2	8.1	14.4	9.5	10.2	12.0	8.6	13.8	5.9	16.1	4.5	17.1

TABLE A-12. BIO-DISC SURFACE AREA AND FLOW COMPUTATIONS FOR OPERATION OF SALINE PILOT PLANT

GEOMETRY

14 disc/stage at 47" diameter

$\frac{\pi d^2}{4}$ = 0.785 3.92 = 12.04 ft^2/side

2 sides = 24.08 ft^2

24 08 x 14 = 337 ft^2/stage

6 stages x 327 = 2023 ft^2/unit

FLOW AND LOADING COMPUTATIONS

(1) 0.25 gal/ft^2/day or 1.33 ℓ/min

(2) 0.5 gal/ft^2/day or 2.66 ℓ/min

(3) 0.75 gal/ft^2/day or 3.98 ℓ/min

(4) 1.0 gal/ft^2/day or 5.32 ℓ/min

(5) 1.5 gal/ft^2/day or 7.97 ℓ/min

(6) 2.0 gal/ft^2/day or 10.60 ℓ/min

(7) 2.5 gal/ft^2/day or 13.29 ℓ/min

(8) 3.0 gal/ft^2/day or 15.95 ℓ/min

(9) 4.0 gal/ft^2/day or 21.26 ℓ/min

(10) 3.5 gal/ft^2/day or 18.60 ℓ/min

(11) 5.0 gal/ft^2/day or 27.58 ℓ/min

(12) 6.0 gal/ft^2/day or 31.90 ℓ/min

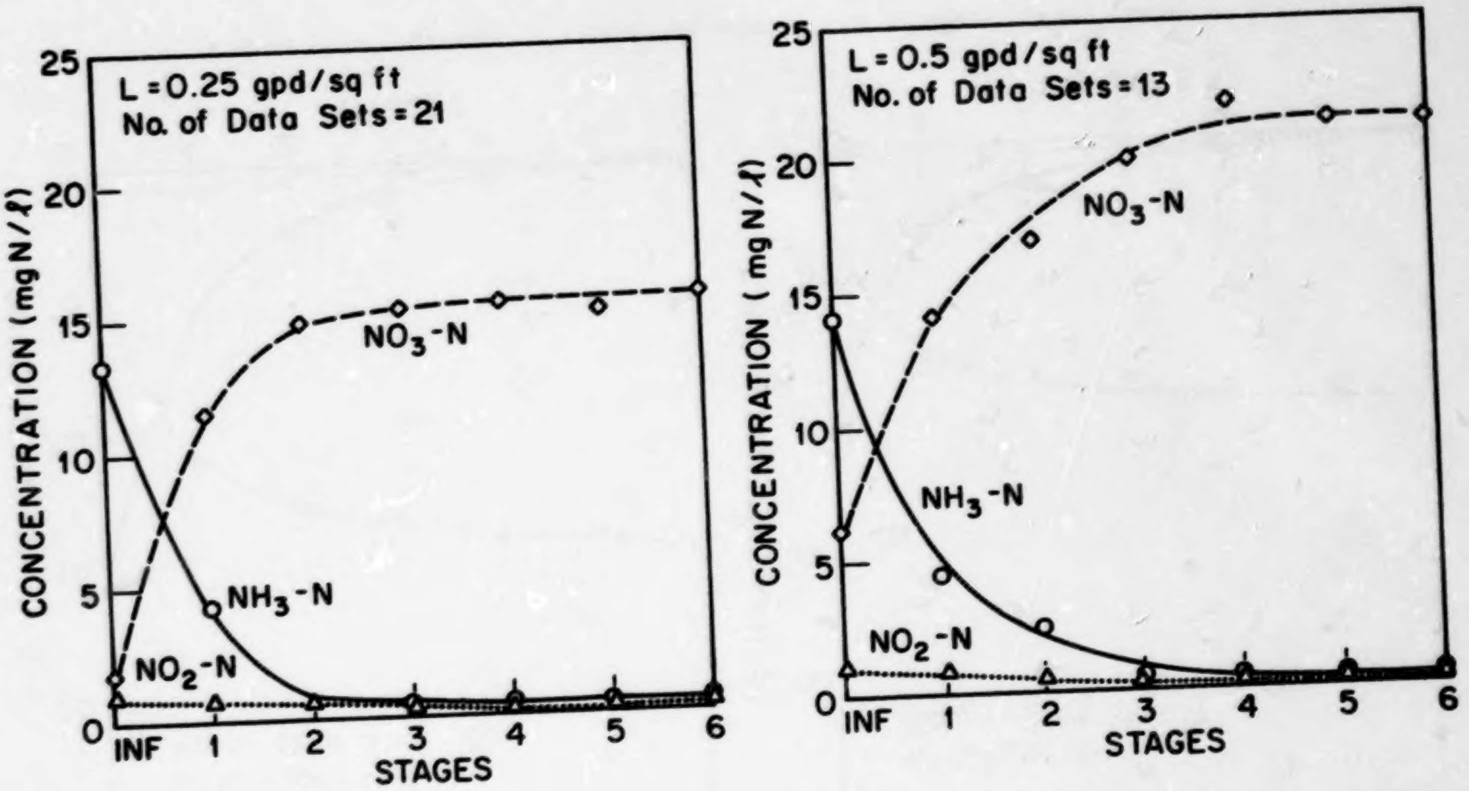


Figure A-1. Profiles of nitrogen concentration in Saline pilot plant.

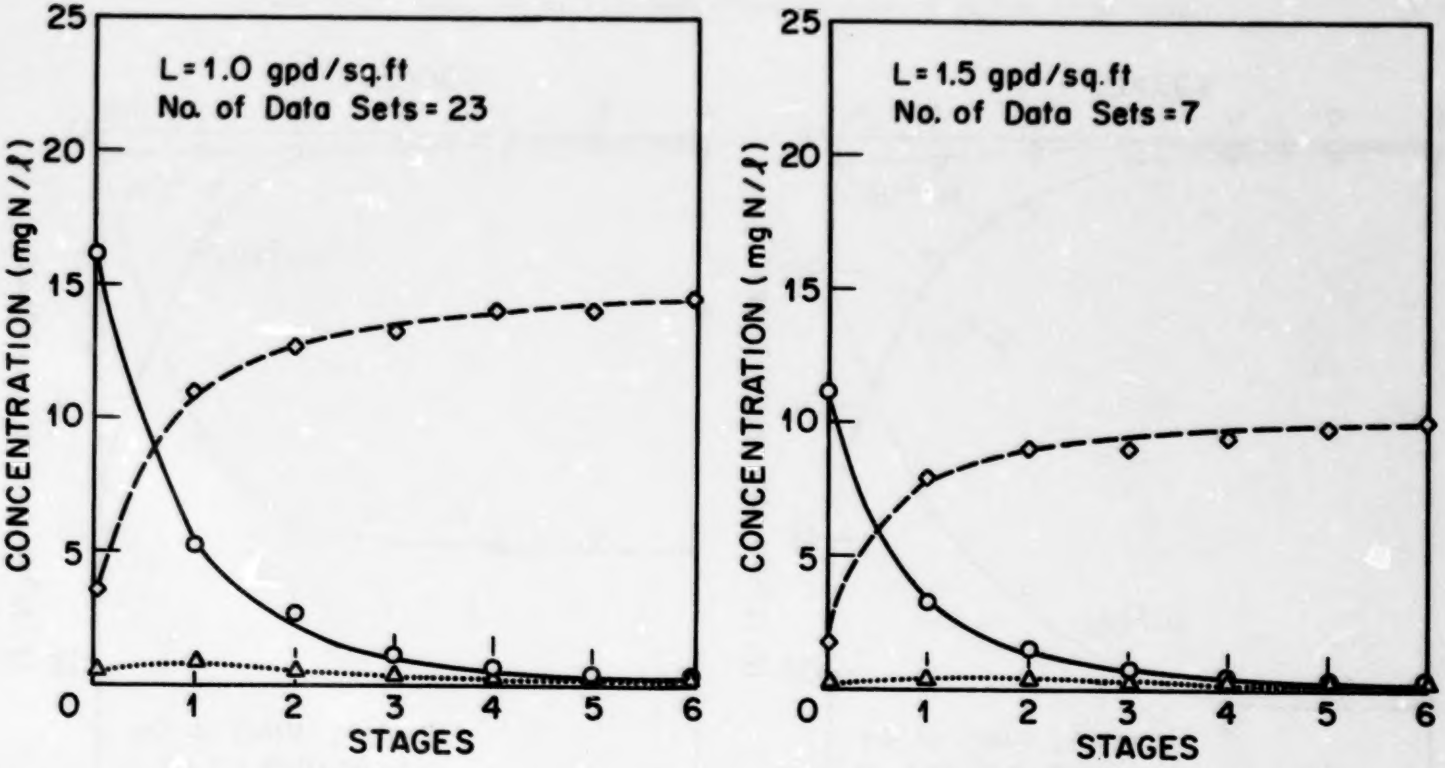


Figure A-2. Profiles of nitrogen concentration in Saline pilot plant.

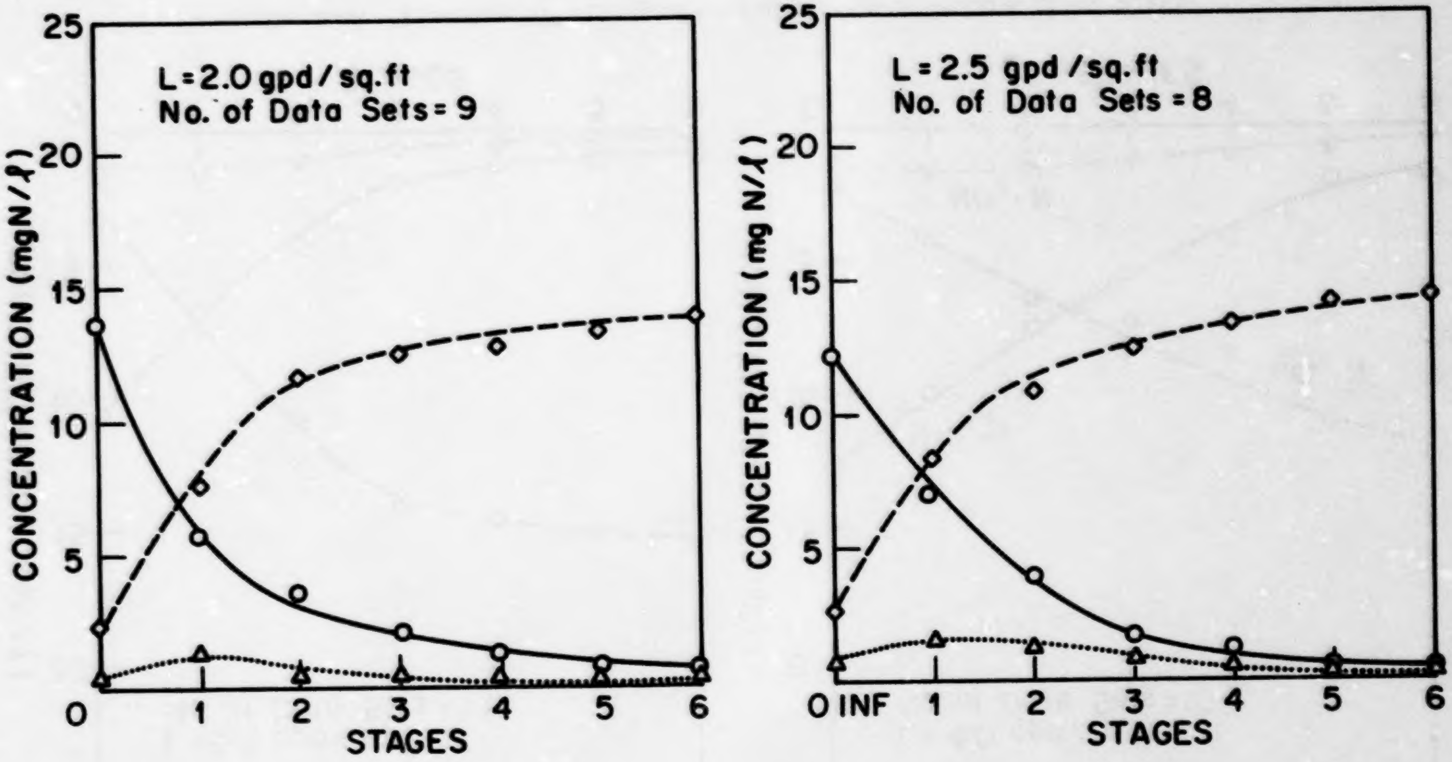


Figure A-3. Profiles of nitrogen concentration in Saline pilot plant.

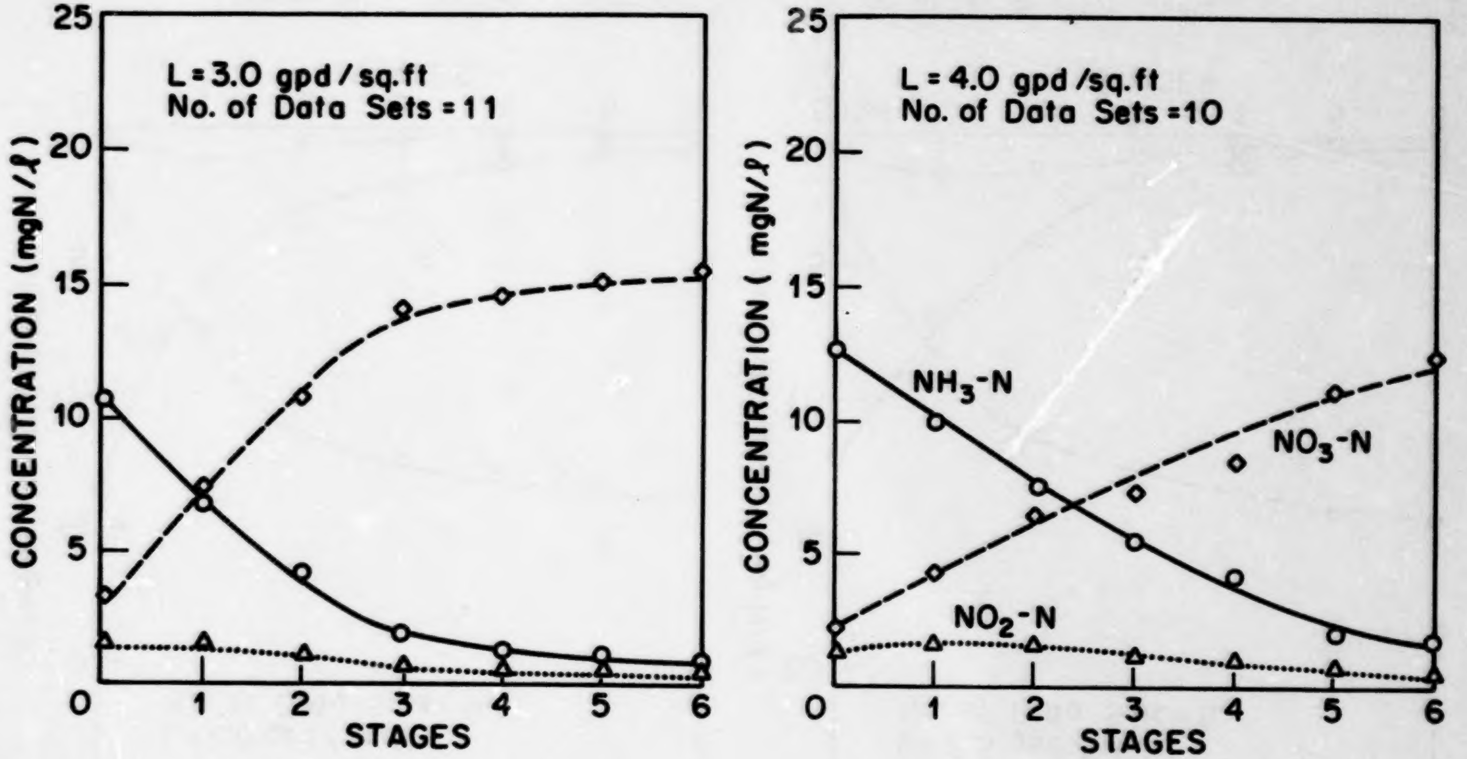


Figure A-4. Profiles of nitrogen concentration in Saline pilot plant.

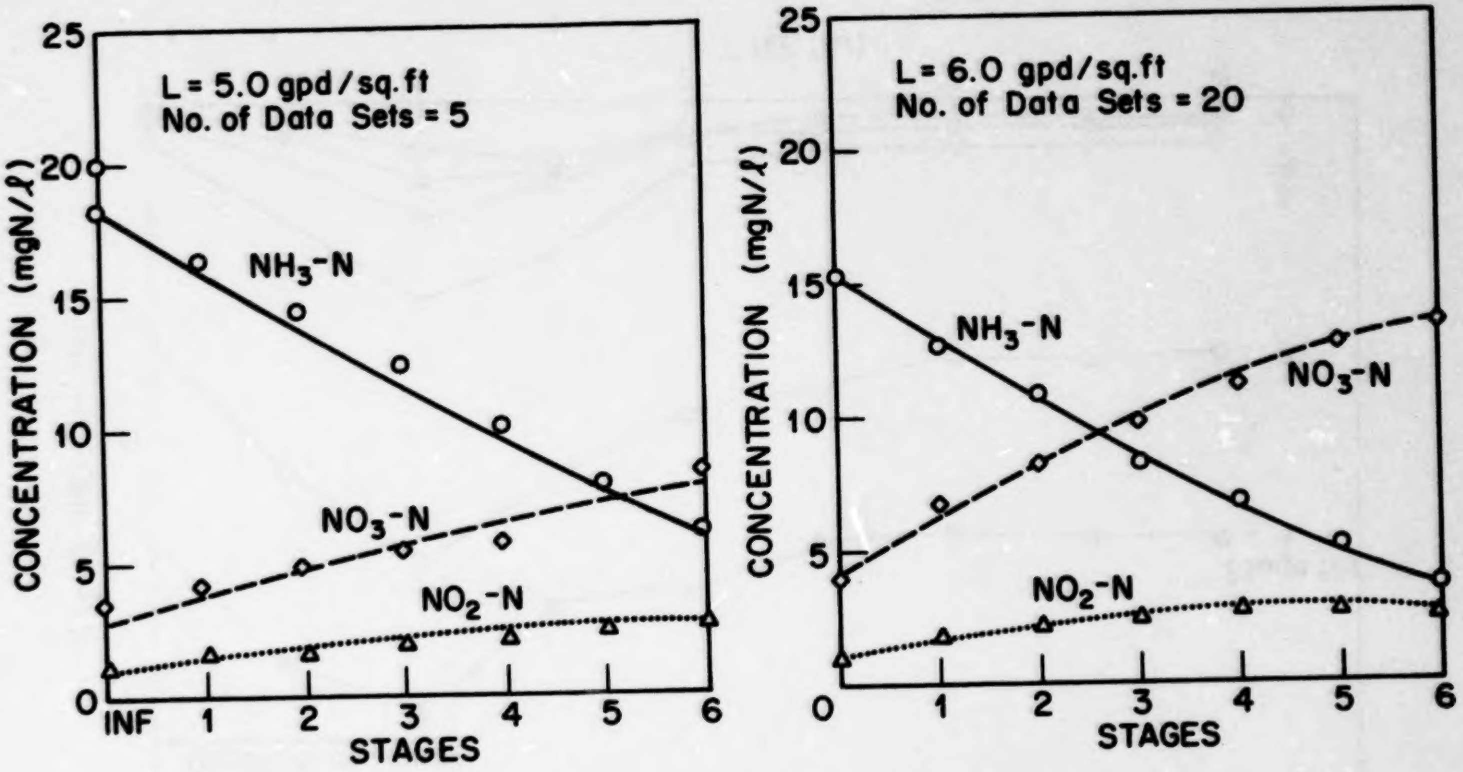


Figure A-5. Profiles of nitrogen concentration in Saline pilot plant.

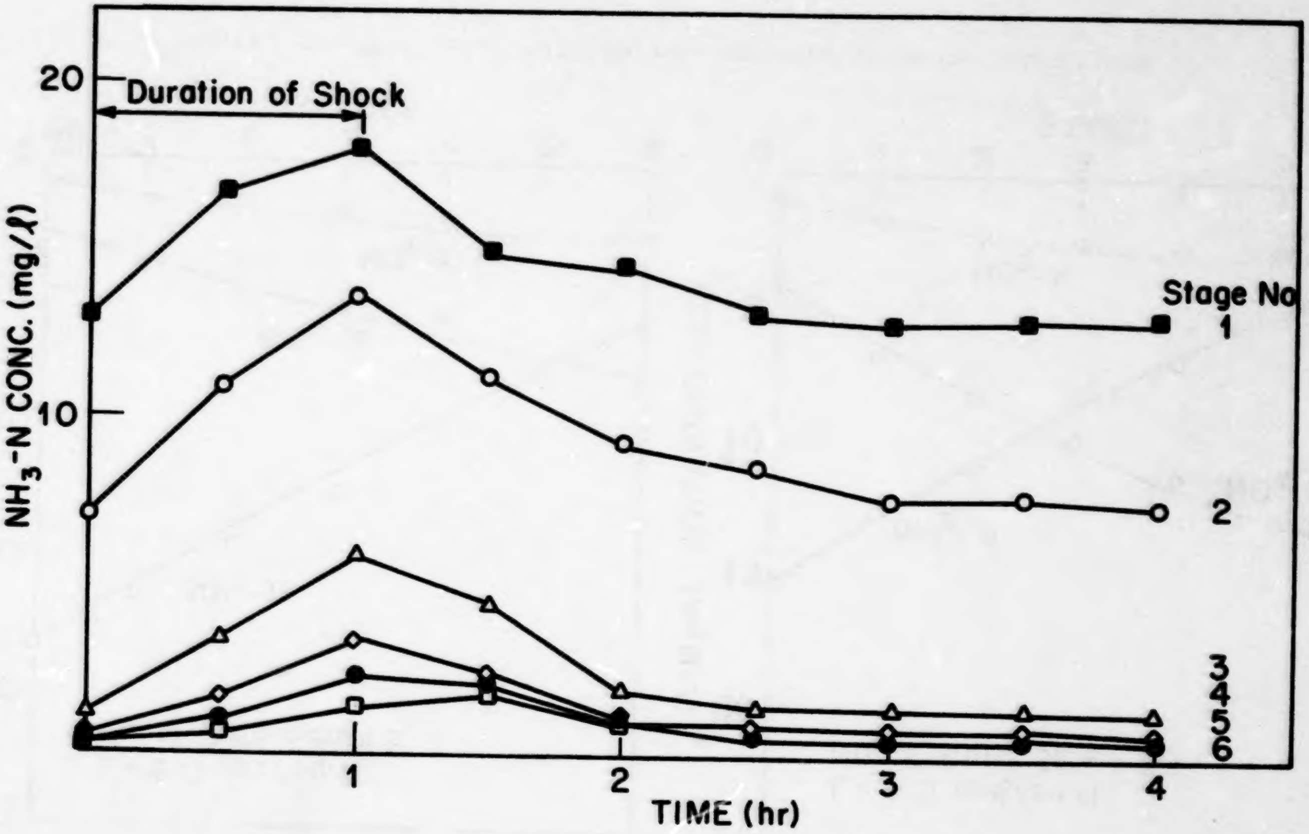


Figure A-6. Run #1202—1-hr flow shock.

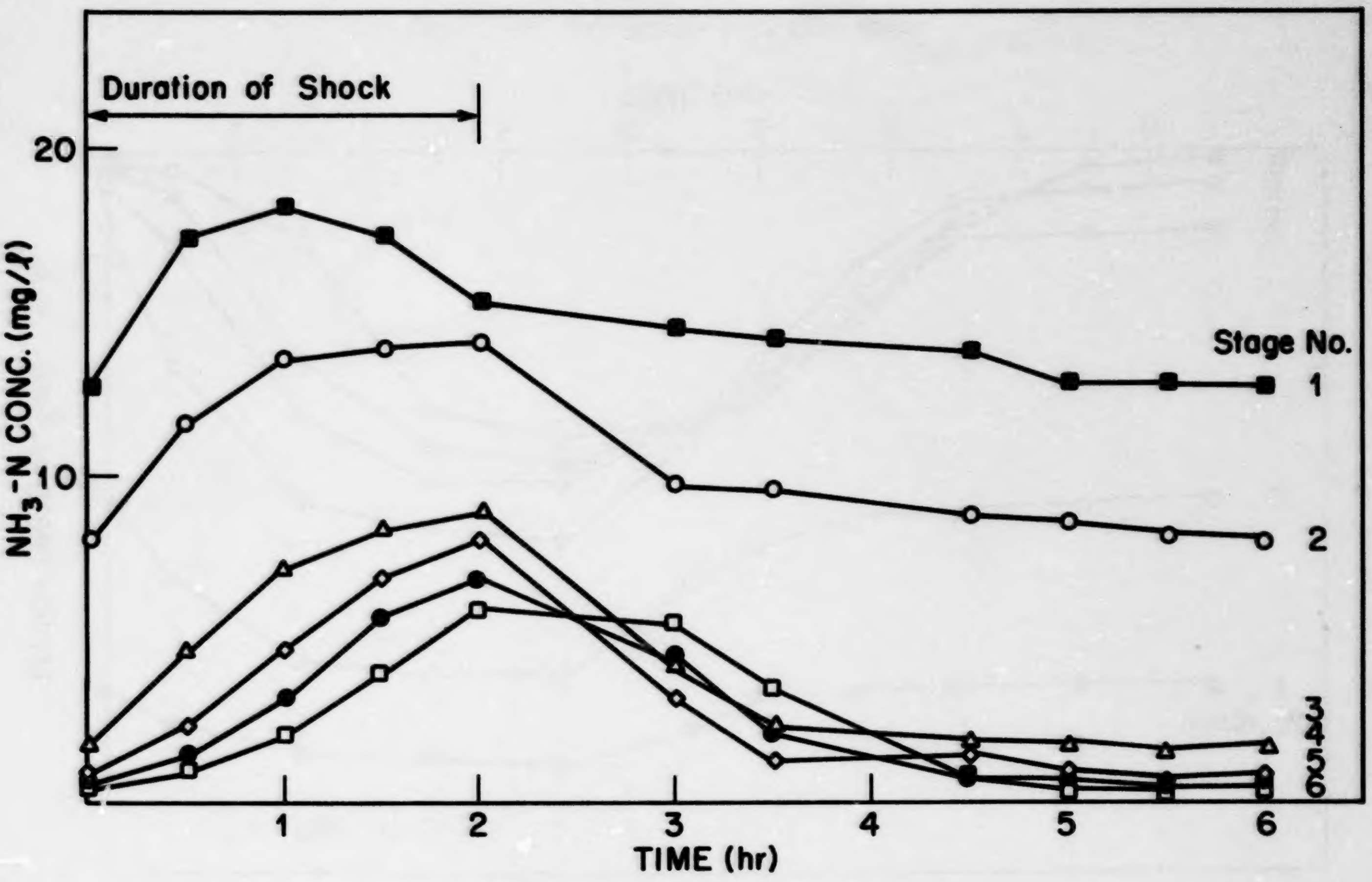


Figure A-7. Run #1130—2-hr flow shock.

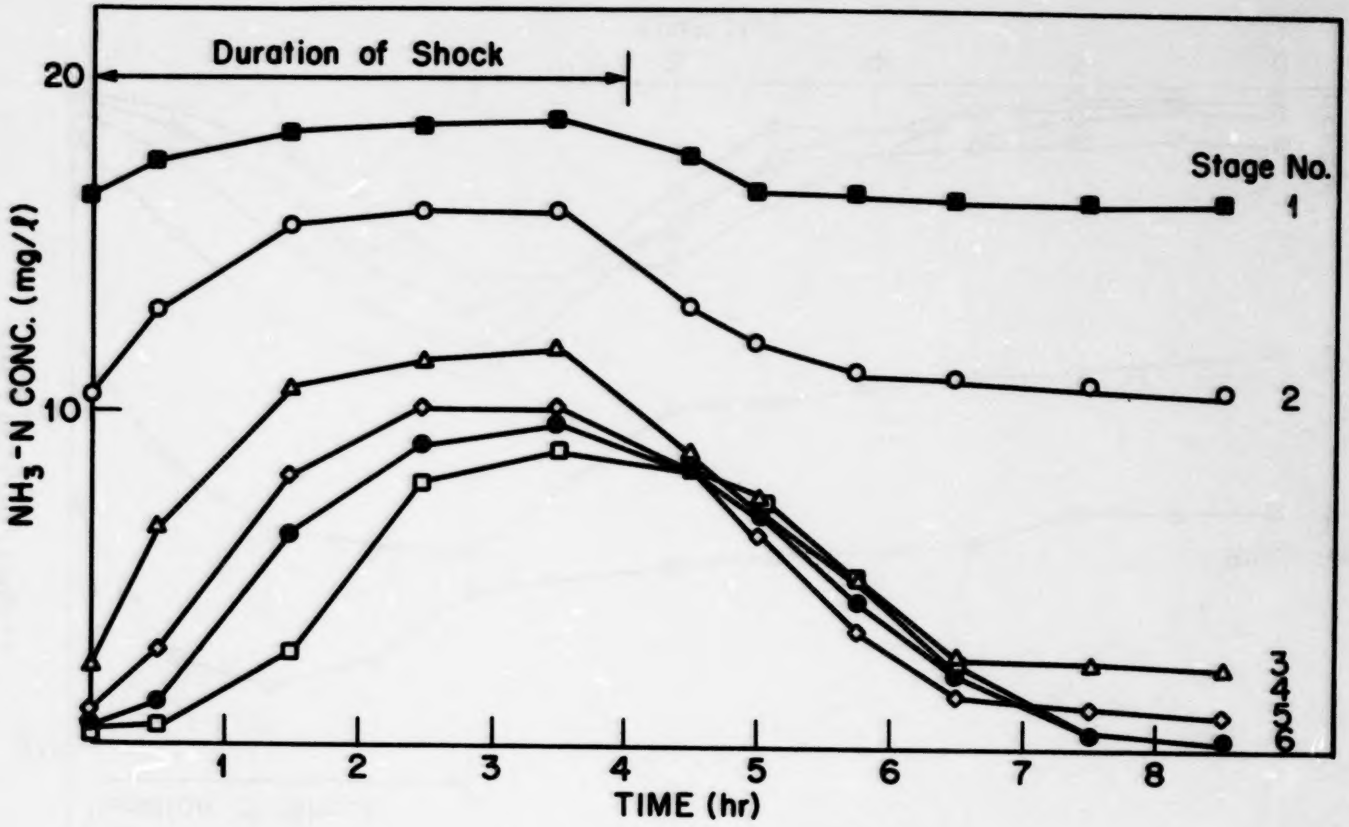


Figure A-8. Run #1102—4-hr flow shock.

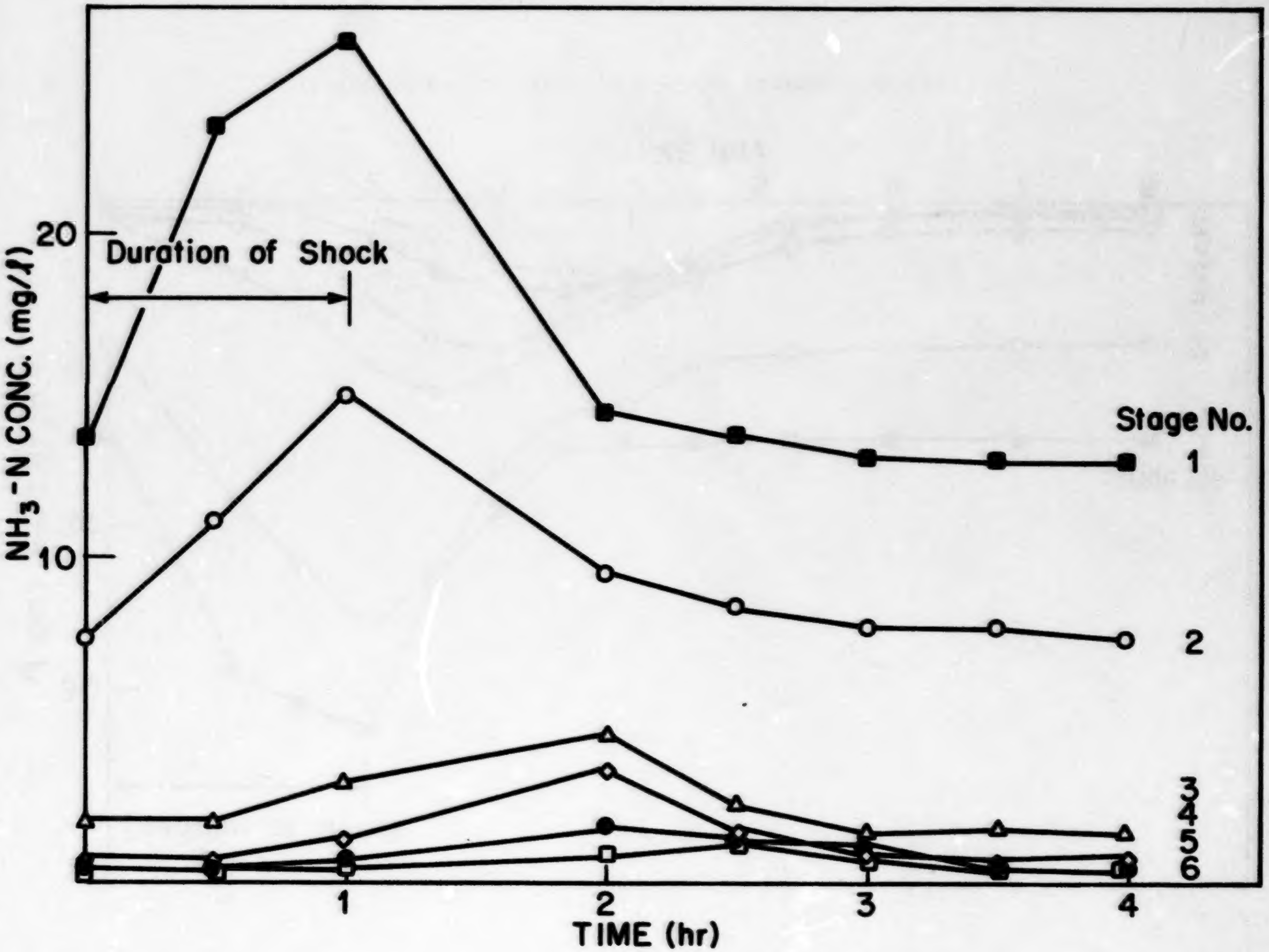


Figure A-9. Run #1026—1-hr strength shock.

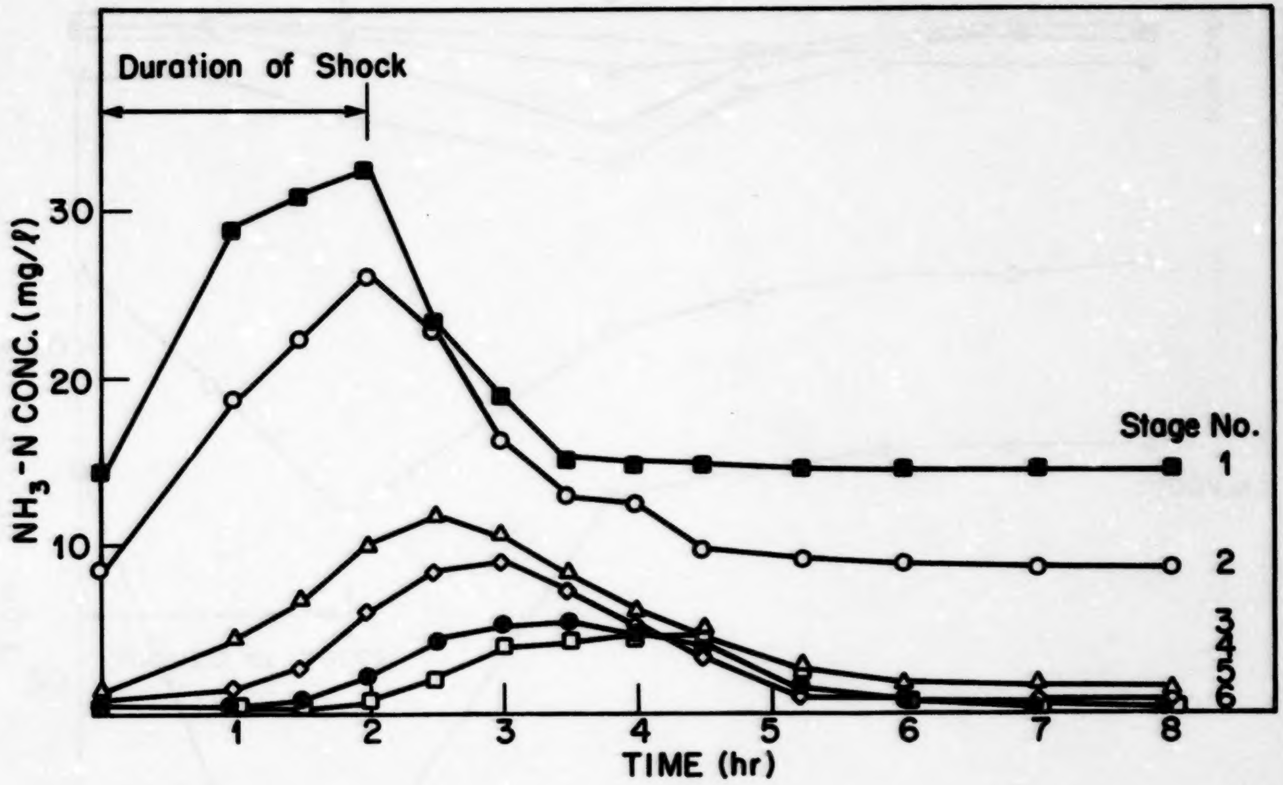


Figure A-10. Run #1028—2-hr strength shock.

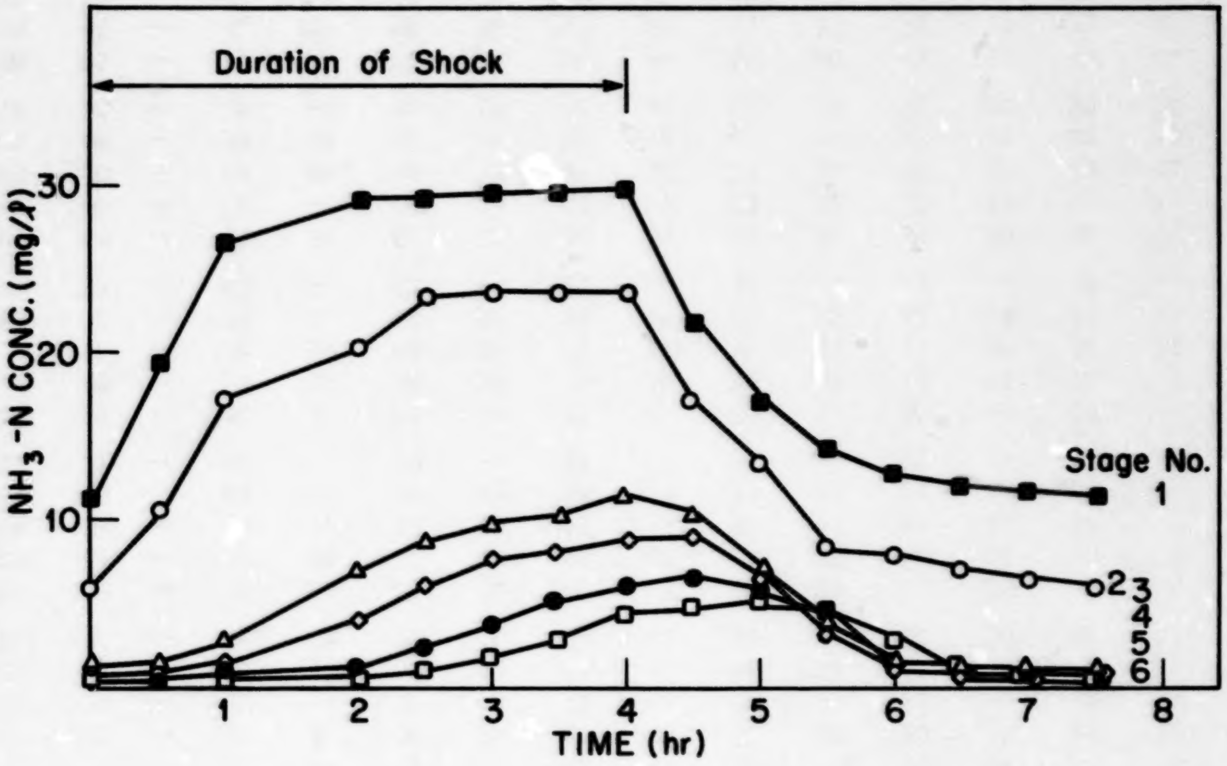


Figure A-11. Run $1104—4-hr strength shock.

APPENDIX B. SUSPENDED SOLIDS AND COD DATA SHEETS—SALINE

TABLE B-1. NITRIFICATION DATA FLOW LOADING = 0.25 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
8/15	77	--	61	--	73	--	42	--	54	--	58	--	--	--
8/18	143	--	67	82	58	24	50	28	81	28	50	34	40	16
8/20	131	--	77	--	77	--	71	--	58	--	71	--	58	--
8/21	81	--	69	38	50	15	65	9	46	44	61	38	42	5
8/26	156	--	86	28	92	18	69	21	65	43	80	36	62	37
8/28	122	--	74	60	65	20	59	18	61	20	65	20	53	9
8/29	83	--	42	26	46	12	31	12	54	28	42	26	50	9
9/04	84	--	38	37	50	13	31	9	32	48	32	40	42	7
9/09	84	--	69	43	38	25	38	35	35	57	31	45	35	15
9/11	88	--	35	--	40	--	35	--	31	--	27	--	35	--
9/12	91	--	30	--	23	--	23	--	23	--	23	--	20	--
9/16	95	--	38	57	34	30	30	34	30	38	19	31	12	19
9/18	76	--	76	39	68	34	61	37	53	34	49	31	46	21
9/20	72	--	76	24	49	32	76	29	61	33	42	46	61	--
9/23	53	--	65	--	22	--	19	--	38	--	15	--	38	--
9/25	65	--	61	62	61	32	61	56	61	33	35	40	46	21
9/27	68	--	42	42	38	18	42	19	38	16	38	19	45	15
9/29	80	--	76	38	49	18	49	12	48	13	49	10	49	11
10/01	65	--	38	49	30	11	27	19	27	17	27	17	27	6
10/16	80	--	68	--	61	19	42	22	42	19	45	24	38	24
10/08	83	--	73	--	41	21	44	25	44	30	44	30	44	--
10/10	69	--	61	103	53	21	33	30	41	29	41	30	37	17
10/13	74	--	78	42	62	37	63	23	50	18	69	32	58	33
10/15	52	--	48	60	44	34	32	35	36	26	40	16	44	19
$\bar{x}$	87	--	60	48	57	23	47	26	46	30	44	30	42	17

TABLE B-2. NITRIFICATION DATA FLOW LOADING = 0.5 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
10/17	50	--	50	48	25	26	33	28	42	23	42	36	29	25
10/20	59	--	59	40	59	12	42	11	46	36	63	32	54	29
10/22	55	--	55	--	42	14	50	21	50	26	42	17	42	20
10/24	45	--	45	35	49	44	61	26	49	--	65	22	40	44
10/27	61	--	57	29	44	12	36	15	52	22	56	19	53	11
10/29	105	--	105	34	73	18	77	20	97	22	60	17	88	14
10/31	39	--	20	26	50	11	23	25	31	17	23	12	27	15
11/03	43	--	46	50	39	12	43	21	39	17	43	16	--	12
11/05	81	--	35	36	43	10	43	21	46	60	46	17	35	23
11/07	75	--	75	42	70	11	63	10	82	44	86	23	73	34
$\bar{x}$	63	--	56	37	49	17	47	16	53	29	53	21	47	23

TABLE B-3. NITRIFICATION DATA FLOW LOADING = 1.0 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
11/19	86	--	90	50	55	34	47	19	71	28	48	30	63	34
12/19	59	--	31	16	43	33	92	10	27	15	47	69	27	21
12/22	67	--	39	39	27	27	47	34	59	68	31	32	27	32
12/24	66	--	66	15	50	30	42	33	56	20	84	20	60	15
12/26	84	--	52	10	68	18	84	43	56	42	48	25	60	21
12/29	80	--	108	18	80	45	40	29	20	43	43	20	16	16
12/31	39	--	43	29	31	19	24	27	39	21	27	7	16	10
1/02	55	--	51	45	47	25	39	25	24	23	35	35	24	18
1/07	118	--	71	14	98	11	75	24	106	57	75	56	67	23
1/14	106	--	--	--	78	38	67	27	51	46	27	33	35	24
1/16	51	--	24	56	24	22	31	33	20	33	24	31	20	22
1/21	141	--	208	55	137	49	110	31	102	65	67	79	71	35
1/23	120	--	85	13	101	31	85	17	70	44	70	44	74	25
1/26	82	--	80	21	70	17	70	17	82	--	66	38	54	27
1/28	97	--	101	15	66	34	89	26	66	70	70	38	70	26
1/30	89	--	120	57	101	58	70	36	70	48	50	33	--	30
2/02	86	--	90	40	71	83	90	43	71	90	47	31	86	35
2/04	86	--	78	--	102	--	94	--	94	--	63	--	63	--
2/06	89	--	82	--	66	--	85	--	70	--	74	--	54	--
$\bar{x}$	83	--	77	31	69	31	68	27	60	42	55	38	50	24

TABLE B-4. NITRIFICATION DATA FLOW LOADING = 1.5 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
2/09	20	--	6	--	5	--	3	--	2	--	2	--	2	--
2/11	82	--	50	2	58	47	66	36	58	42	50	49	70	33
2/13	85	--	66	36	82	44	27	39	47	32	39	43	47	17
2/16	39	--	43	50	66	42	62	44	43	16	27	39	31	20
2/18	31	--	121	29	39	39	35	--	23	41	58	33	58	27
2/20	74	--	70	37	51	30	--	--	43	21	43	34	43	15
2/23	39	--	47	20	55	25	31	27	39	25	27	27	31	19
2/25	55	--	62	26	23	38	27	31	27	37	47	35	35	23
2/27	39	--	35	40	4	41	35	31	12	41	63	58	59	30
$\bar{x}$	52	--	56	33	43	38	36	35	33	32	40	40	42	23

TABLE B-5. NITRIFICATION DATA FLOW LOADING - 2.0 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
3/10	48	--	24	25	--	32	20	40	20	42	16	37	16	19
3/12	40	--	32	26	16	33	32	38	16	33	--	43	--	18
3/15	88	--	36	20	36	30	38	30	36	37	23	29	23	24
3/17	44	--	39	18	33	22	38	24	27	29	27	29	27	19
3/19	44	--	38	22	38	25	38	24	33	37	33	42	33	18
4/05	63	--	46	45	35	65	31	47	46	47	27	--	27	45
4/16	56	--	44	--	24	--	24	--	28	--	36	--	40	--
4/21	96	--	48	54	36	41	36	90	23	50	42	77	56	38
4/30	46	--	32	27	28	32	32	40	32	29	40	33	20	29
$\bar{x}$	58	--	38	30	31	35	32	42	30	38	29	41	28	26

TABLE B-6. NITRIFICATION DATA FLOW LOADING = 2.5 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
5/10	40	--	37	24	37	30	35	20	37	30	35	27	32	20
5/14	36	--	28	33	28	25	24	28	24	25	24	23	20	22
5/19	56	--	36	23	32	25	36	36	32	41	28	38	28	23
5/21	60	--	52	25	48	35	48	38	40	40	40	35	36	33
5/24	56	--	52	--	48	--	48	--	44	--	44	--	36	--
5/28	47	--	36	--	32	--	28	--	32	--	24	--	20	--
6/01	47	--	37	--	28	--	24	--	32	--	24	--	24	--
6/07	55	--	39	--	31	--	29	--	31	--	28	--	20	--
$\bar{x}$	50	--	40	26	36	29	29	34	31	34	31	31	27	25

TABLE B-7. NITRIFICATION DATA FLOW LOADING = 3.0 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
6/16	51	--	53	--	43	--	39	--	39	--	35	--	35	--
6/18	51	--	51	--	47	--	39	--	35	--	31	--	27	--
6/21	82	--	74	--	55	--	43	--	47	--	43	--	31	--
6/23	51	--	51	--	47	--	43	--	39	--	39	--	35	--
6/30	27	--	23	--	20	--	20	--	20	--	20	--	16	--
7/02	43	--	35	--	35	--	31	--	27	--	27	--	23	--
7/05	54	--	46	--	46	--	42	--	38	--	35	--	35	--
7/08	54	--	50	--	42	--	42	--	35	--	35	--	31	--
7/14	51	--	47	--	43	--	35	--	35	--	31	--	31	--
7/19	47	--	39	--	27	--	27	--	23	--	23	--	--	--
7/21	46	--	46	--	38	--	42	--	42	--	42	--	36	--
$\bar{x}$	50	--	45	--	40	--	37	--	34	--	32	--	29	--

TABLE B-8. NITFICIATION DATA FLOW LOADING = 4.0 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
7/26	50	--	54	--	38	--	34	--	34	--	28	--	24	--
7/30	54	--	54	--	42	--	42	--	38	--	34	--	34	--
8/02	42	--	30	--	30	--	22	--	20	--	16	--	16	--
8/06	38	--	34	--	42	--	42	--	42	--	27	--	27	--
8/09	25	--	35	--	31	--	25	--	35	--	31	--	19	--
8/11	36	--	32	--	32	--	28	--	28	--	20	--	20	--
8/13	36	--	32	--	32	--	26	--	20	--	20	--	16	--
8/16	51	--	47	--	40	--	44	--	40	--	40	--	40	--
8/18	41	--	36	--	33	--	20	--	16	--	20	--	16	--
8/23	24	--	24	--	32	--	24	--	28	--	20	--	20	--
8/25	44	--	40	--	40	--	36	--	32	--	32	--	20	--
$\bar{x}$	40	--	38	--	36	--	31	--	30	--	26	--	23	--

TABLE B-9. NITRIFICATION DATA FLOW LOADING = 5.0 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
9/03	31	--	27	--	27	--	27	--	27	--	23	--	23	--
9/07	38	--	35	--	35	--	31	--	27	--	27	--	21	--
9/08	31	--	23	--	23	--	23	--	19	--	19	--	15	--
9/10	35	--	27	--	27	--	23	--	23	--	19	--	19	--
9/13	31	--	27	--	27	--	27	--	23	--	23	--	23	--
9/15	35	--	35	--	31	--	31	--	29	--	27	--	23	--
$\bar{x}$	33	--	29	--	28	--	27	--	25	--	23	--	21	--

TABLE B-10. NITRIFICATION DATA FLOW LOADING = 6.0 gpd/ft^2

Date	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS	COD	SS
9/17	17	--	17	--	17	--	18	--	18	--	18	--	13	--
9/20	35	--	31	--	31	--	27	--	27	--	23	--	23	--
9/23	43	--	41	--	21	--	33	--	33	--	25	--	25	--
9/27	34	--	27	--	27	--	27	--	22	--	21	--	21	--
9/29	18	--	15	--	18	--	10	--	11	--	14	--	17	--
10/01	38	--	--	--	34	--	29	--	32	--	29	--	26	--
10/05	32	--	34	--	34	--	32	--	30	--	24	--	24	--
$\bar{x}$	31	--	28	--	26	--	25	--	24	--	22	--	21	--

TABLE C-1 NITRIFICATION DATA FLOW LOADING = 0.25 gpd/ft^2

Date	Lagoon		S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	NH_3		NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
5/11	0.2	0.6	--	--	1.8	7.2	0.8	6.9	0.7	7.4	0.3	7.4	0.3	7.1	0.3	7.6
5/17	0.2	0.1	--	--	5.5	10.2	3.3	11.2	1.3	12.3	0.7	13.1	0.4	12.6	0.4	13.1
5/28	0.3	0.1	19.0	1.6	9.6	11.7	8.4	11.9	5.8	15.0	4.4	15.3	3.5	15.3	3.1	16.0
6/01	0.3	0.1	33.0	0.1	5.4	14.3	3.8	14.9	1.5	17.1	0.7	17.3	0.6	17.5	0.4	17.8
6/04	0.3	0.1	18.5	3.1	4.7	10.5	3.9	13.2	1.1	18.9	0.5	18.0	0.3	19.2	0.2	20.4
$\bar{x}$	0.3	--	--	--	4.4	10.5	3.0	11.5	1.1	13.9	0.6	13.9	0.4	14.1	0.3	14.7

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of $(NO_3 + NO_2)$ mg/ℓ as N.

TABLE C-2. NITRIFICATION DATA FLOW LOADING = 0.5 gpd/ft^2

Date	Lagoon		S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	NH_3	N_{ox}	NH_3*	N_{ox}†	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}	NH_3	N_{ox}
6/08	0.6	0.2	16.6	0.2	5.6	9.0	4.0	10.2	1.8	12.6	1.4	13.0	1.0	13.5	0.8	13.5
6/22	0.6	0.1	15.1	1.4	8.6	8.3	7.3	10.0	6.8	10.5	3.2	13.0	2.1	13.5	1.1	13.9
6/25	0.3	--	12.9	--	4.6	--	3.5	--	1.1	--	0.6	--	0.4	--	0.3	--
6/29	0.4	0.1	12.0	1.0	4.7	11.0	3.6	12.2	1.6	14.8	0.8	15.0	0.4	15.1	0.5	15.5
7/02	0.3	0.1	18.8	3.0	9.2	11.2	8.0	13.1	3.0	17.1	1.0	19.3	0.5	20.1	0.4	20.4
7/09	0.6	0.1	11.2	2.1	4.0	9.7	2.5	11.2	1.2	13.0	1.1	13.0	0.5	13.4	0.5	13.5
7/13	0.7	0.1	11.1	2.8	4.8	8.2	3.4	10.2	2.4	10.2	0.7	12.7	1.1	13.2	0.4	13.3
$\bar{x}$	0.5	--	13.9	1.8	5.9	9.6	4.6	11.1	2.5	13.0	1.3	14.3	0.9	14.7	0.6	14.9

*NH_3 where used this term expresses NH_3 mg/ℓ as N.

†N_{ox} where used this term expresses the sum of (NO_3 + NO_2) mg/ℓ as N.

TABLE C-3. GENOA TEMPERATURES, °C

Date	Outside	Inside	Lagoon*	Inflow† (Stage 1)	Overflow (Stage 6)
1/05	-7	4	Frozen	0	--
1/06	-2	8	Frozen	0	--
1/08 (7 pm)	-10	2	Frozen	0	--
1/08	-13	-2	Frozen	0	--
1/09	-13	-3	Frozen	0	--
1/09 (7 pm)	-12	13	Frozen	0	--
1/12	-3	7.5	Frozen	0+tank thawed	--
1/15	-4	7	Frozen	0+tank thawed	--
1/19	-0.5	7.5	Frozen	0+tank thawed	--
1/22	-6	6	Frozen	Tank 3°	--
1/27	-5	10	Frozen	0	0
2/05	-6	12	Frozen	0-1	1
2/10	7	10	Frozen	3	3
2/13	9	9	Frozen	5	5
2/18	12	11.5	50% frozen	7	7
2/20	9	11	Free of ice	6	7
2/24	8	9	3	4	4
3/02	4	9.5	6	6.5	7
3/08	4	8	4.5	4.5	5
3/11	3.5	11	4	4	--
3/17	-1	10	2	2	--
3/23	13	13.5	10	11	11
3/25	17	17.5	13	13	14
3/30	25	20	15	15	16
4/02	13.5	17	8.5	11.5	13
4/06	13.5	16.5	8	15	16
4/09	10.5	16.5	11.5	15.5	15.5
4/13	16.5	16.5	12.5	12	12.5
4/16	28	22.5	20	19	19
4/20	19	19	20	20	19
4/23	17.5	18	18	16.5	16
4/27	9	15.5	9.5	9.5	9.7
5/06	9	15	14	15	15
5/11	19	17	18	16.5	16
5/14	22	19	18.5	18	18
5/17	20	19	20	18	18
5/24	23	19	19	18	18

*Lagoon temperatures taken near shore and near lagoon overflow.

†Tank temperatures of 0°C usually meant some ice in tank.

APPENDIX D. PILOT PLANT LAYOUT

TABLE D-1. SPECIFICATION FOR REACTORS

1. Tank—steel epoxy coated
   5'-4" wide, 2'-0" deep, 9'-4" long. The tank was braced and supported on 2' legs of angle iron. Two 1" nipples welded to the tank and provided with male pipe thread.

2. Concrete fillets 15" x 15" and 3" x 3" cast of light weight concrete coated with paraffin and 9" long. Thus two fillets slip into each stage to support the removable partitions (12 large and 12 small required).

3. Tank fitted snugly with five 1/2" portable partitions. These will be supported by the concrete fillets on each side. All to be sealed in place with plastic modeling clay. A 1" hole will be cut at the point indicated on Figure D-1.

4. Tank will be equipped with 3" channels welded to each end to support 1" ball bearings and 1" steel shaft.

5. Shaft to be equipped with 90 discs, 1/2" thick, and 4'-0" diameter. Discs to be constructed of foamed polystyrene at a density of ~ 4 lb/ft^3. Spacing in each stage is as follows:

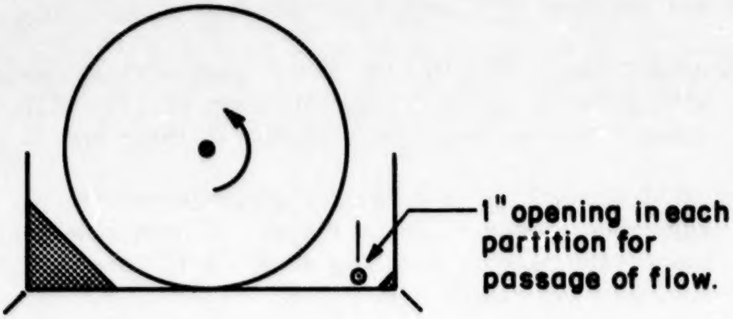
   each disc = 1/2" ——— 15 at 1/2" = 7.5"
   each space = 5/8" ——— 14 at 5/8" = 8.75"
   end clearances = 1" ——— 2 at 1" = 2.0"
   Total = 1'-6-1/4"

   6 such stages = 109-1/2"
   5 partitions at 1/2" = 2-1/2"

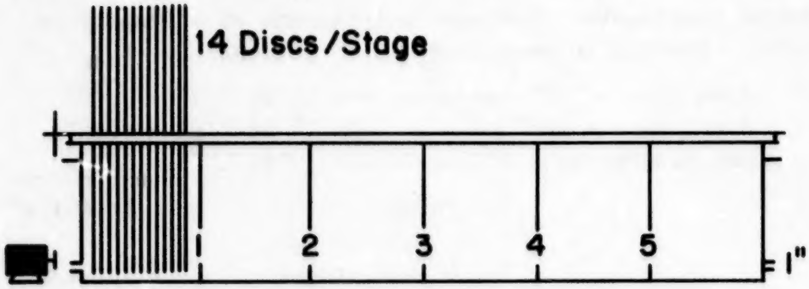
   Total inside dimension = 112"

6. The 1" steel shaft shall be equipped with a chain drive and sprockets. A variable speed motor will provide rotation with continuously varying speeds up to at least 12 rpm.

7. Seven sampling ports shall be provided at the points indicated on Figure D-2. These shall consist of stuffing boxes which will permit the insertion of glass sampling tubes into the reactor at points 2 - 6. Points 1 and 7 shall consist of 3/8" pipe fittings tapped into inlet and outlet nipples.

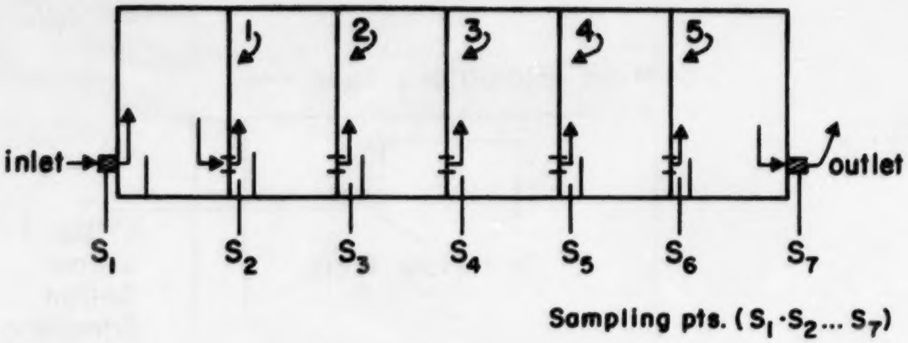

1" opening in each partition for passage of flow.

CROSS SECTION OF REACTOR

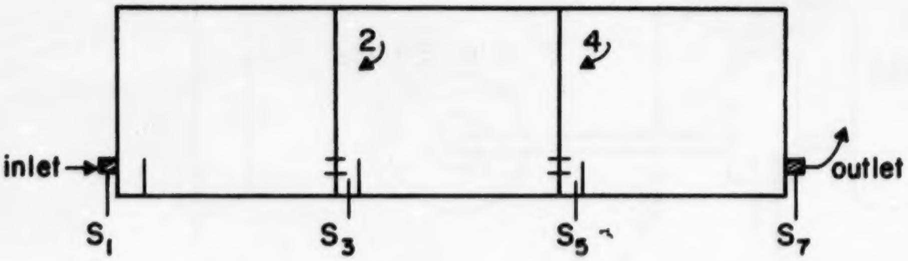

14 Discs/Stage
1
2
3
4
5
1"

LONGITUDINAL CROSS SECTION

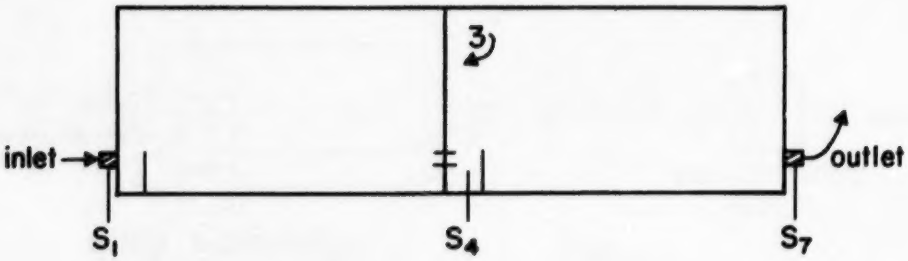
Figure D-1. Rotating biological surface units.


1
2
3
4
5
inlet
outlet
S1
S2
S3
S4
S5
S6
S7
Sampling pts. (S1 · S2 ... S7)

Six Stages in Series

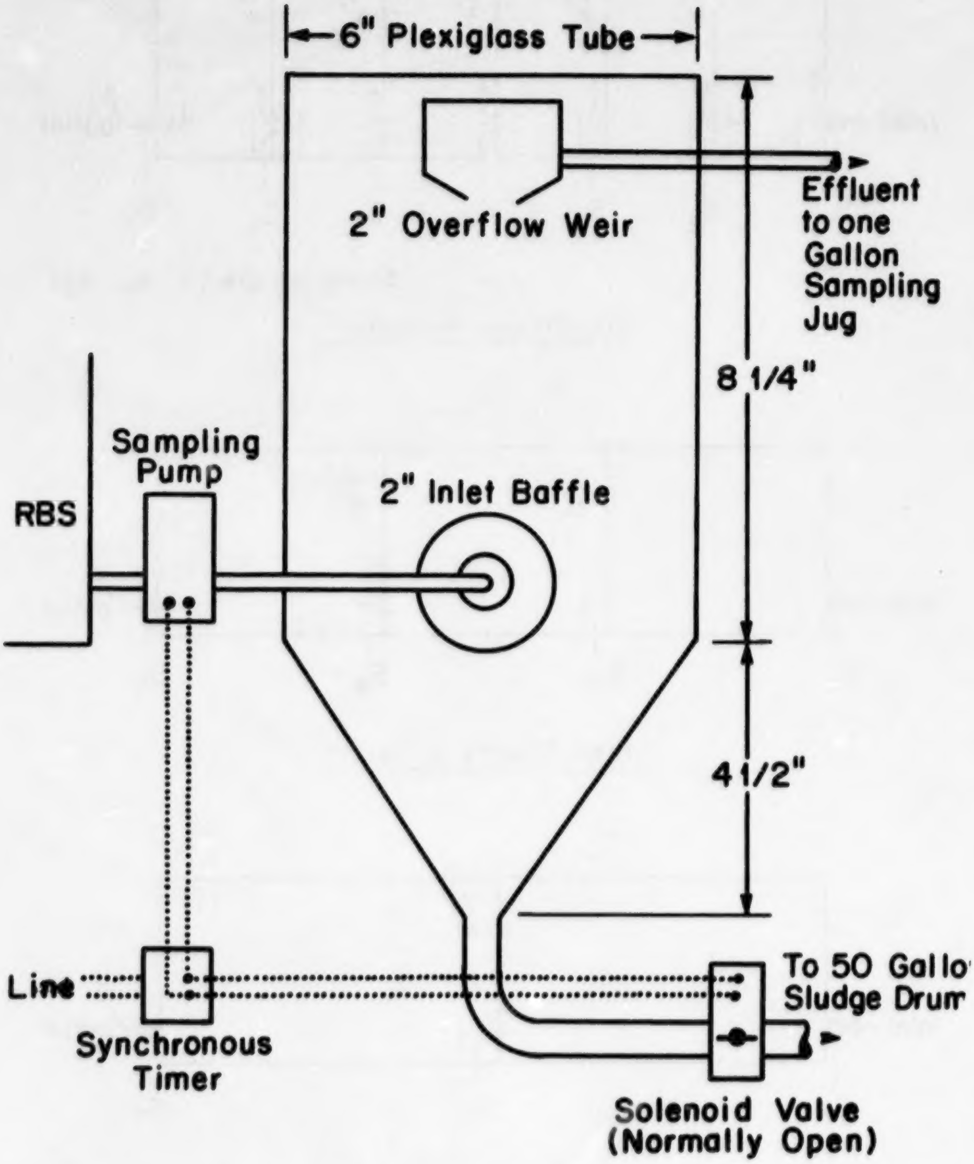

2
4
inlet
outlet
S1
S3
S5
S7

Three Stages in Series


3
inlet
outlet
S1
S4
S7

Two Stages in Series

Figure D-2. Cross section of reactor.



6" Plexiglass Tube
2" Overflow Weir
Effluent to one Gallon Sampling Jug
8 1/4"
Sampling Pump
RBS
2" Inlet Baffle
4 1/2"
Line
Synchronous Timer
To 50 Gallo
Sludge Drum
Solenoid Valve (Normally Open)

Figure D-3. Plan of settling tube sampler.

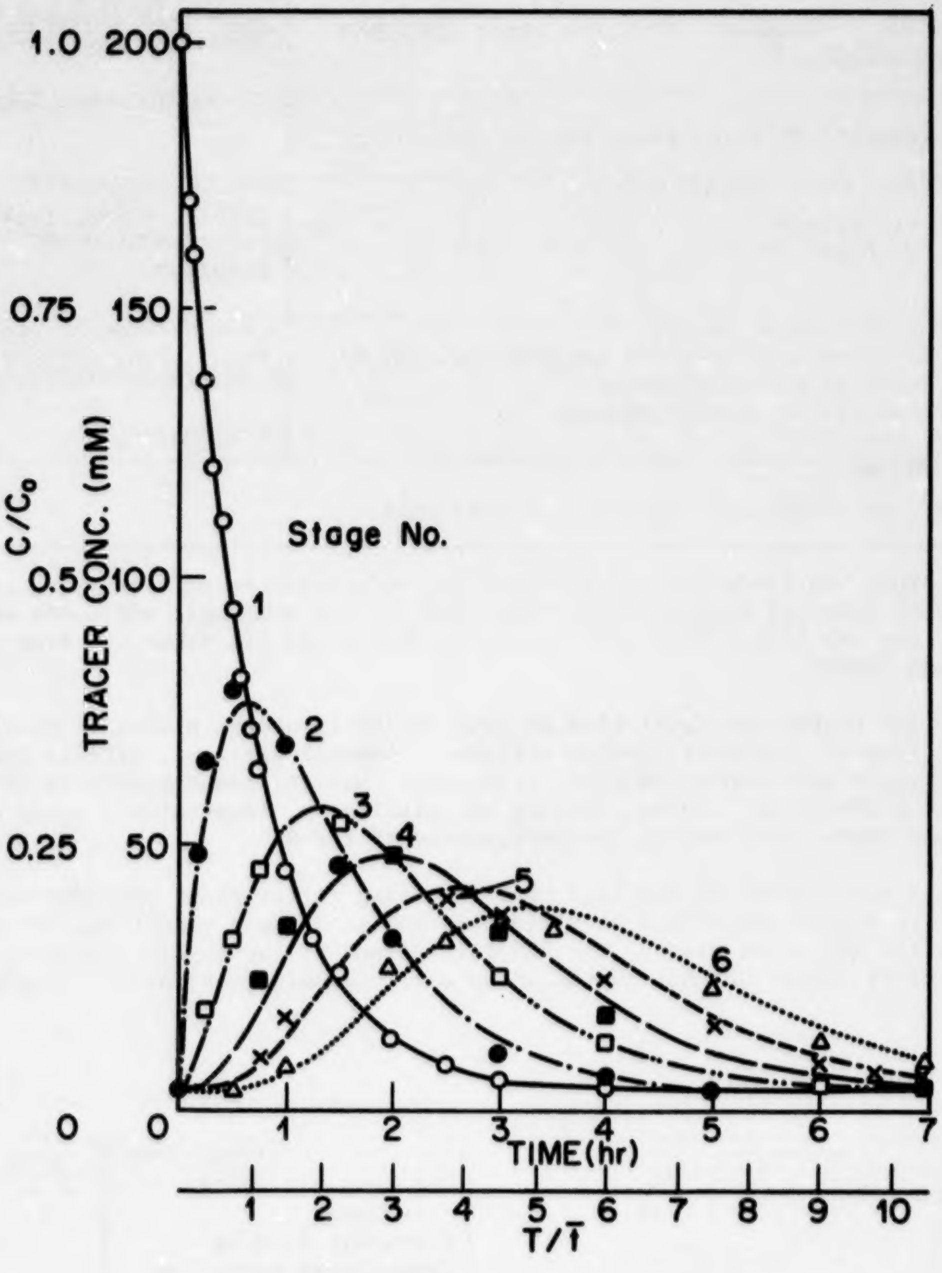


Figure D-4. Six-stage tracer study.